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Formation of Parasequence-like Successions at Different Depositional Hierarchical Scales

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ABSTRACT: The interpretation of parasequences is often complicated by ambiguities in the definition of key surfaces, uncertainties in interpretation of facies successions, varying data quality, and different rules of thumb (heuristics) used for identification. The number of interpreted parasequences in an area can, for example, be directly influenced by factors such as the number of data points, the spatial coverage, and the depositional processes governing sedimentation. While abrupt deepening events associated with flooding surfaces may occasionally be identified objectively through vertical facies relationships, they are often inferred, which leads to both allogeneic and autogenic successions being treated as parasequences. This paper explores the various mechanisms that produce shallowing-upward successions that can resemble parasequences across different depositional hierarchy levels, including: (1) allogenic changes in the balance between rates of sediment supply and accommodation, (2) autogenic trunk channel avulsions driving significant sediment redistribution at the shoreline, and (3) local-scale autogenic processes, such as levee and barrier breaches near river mouths. Modern examples of each type are provided, and their implications for interpreting ancient parasequences are discussed. It is argued that misinterpretation of the hierarchy level of such parasequence-like successions can significantly impact the selection of depositional analogues and the reconstruction of depositional history of an interval. Although each mechanism discussed may result in architectural units resembling parasequences, we recommend that the term "parasequence" be reserved for only regressive-transgressive units formed on a regionally significant scale, while alternative terminology should be used for intra-depositional system deposits formed on a more local scale.

INTRODUCTION

There has been a long history of debate regarding the definition and utility of parasequences. Definition ambiguities, especially regarding bounding surfaces, have been widely discussed (see Posamentier and Allen, 1999; Catuneanu, 2006, 2019; Catuneanu and Zecchin, 2013, 2000). It has been pointed out that parasequences are not defined in a consistent manner between case studies and that different numbers of parasequences have been interpreted in the same areas by various researchers (Colombera and Mountney, 2020). There is a noted discrepancy between parasequence scales in outcrops and subsurface, with the latter generally being larger (Colombera and Mountney, 2020). It has been argued that intervals resembling parasequences can represent different architectural scales and can be generated by both allogenic and autogenic processes (Catuneanu et al., 2009; Miall, 2010; Catuneanu, 2019). This has led some workers to suggested restricting the term to only certain temporal and stratigraphic scales (Hampson et al., 2008, Ainsworth et al., 2020), while other have proposed abandoning the term altogether (Miall, 2010; Catuneanu and Zecchin, 2013, 2020, Catuneanu, 2019). Depending on the type of deposit being described, successions that resemble parasequences has been described as 'bedsets', 'high-resolution sequences', and the more generic 'small-scale cycles' or 'allomembers'.

The use of parasequences to subdivide stratigraphy below the depositional sequence scale is nonetheless widely adopted and has significant practical utility. For example, subdividing intervals based on flooding surfaces, typically characterized by fine-grained layers that greatly affect fluid flow in the subsurface, can be used to subdivide hydrocarbon reservoirs into vertical flow units (Ainsworth, 2010, Magalhães et al., 2021). Similar principles can be applied to understanding plume migration at CO2 injection sites or improving groundwater resource management and contaminant transport. Using units that can be easily related to fluid flow is particularly useful for cross-disciplinary teams, where not all members will be geologists. An additional value is that parasequences force workers to think chronostratigraphically and in three dimensions. The widespread adoption of the parasequence term in the hydrocarbon industry should be considered as a testament to its value.

The notion of parasequences do nonetheless have serious issues that should not be disregarded. Practical problems with inconsistent mapping of parasequences, for example, arise when attempting to apply key insights from one site to another. Resolving stratigraphic architecture, particularly in the subsurface where data is always scarce, often depends on the use of depositional analogues to fill information gaps (Reynolds, 1999; Sech et al., 2009; Howell et al, 2014; Colombera and Mountney, 2020; Ainsworth et al., 2020). As a result, we frequently rely on the depositional characteristics and dimensions of parasequences from other case studies to reduce uncertainty, a practice that often holds significant economic and practical value. For example, we might want to use a database of parasequence dimensions to address questions about the correlatability of fine-grained intervals tied to flooding surfaces. These decisions, in turn, influence how we define flow units within a reservoir. However, this effort becomes difficult if the collected parasequence dimensional data is based on architectural units mapped using inconsistent methodologies or limited data.

This paper focuses on one key aspect that leads to parasequence ambiguity in clastic systems, that is, the common practice of defining parasequences at different hierarchical architectural levels. While we argue that true parasequences should be defined on only one of these levels, we will nonetheless discuss the other deposits as being "parasequence-like" to communicate that they share many characteristics with parasequences and can potentially be interpreted as such by workers. Since some of the mechanisms discussed that can form parasequence-like successions are autogenic in origin and, therefore, strongly depend on the nature of their parent depositional system, we do not consider such deposits to be scale and time independent.

This paper has the following objectives:

- To discuss the various mechanisms that can lead to the formation of shallowing-upward successions, which may be potentially interpreted as parasequences.
- To explore the practical implications of misinterpreting these mechanisms.
- To draw lessons from modern systems to propose alternative interpretations for ancient successions that may be misinterpreted as parasequences.

SOURCES OF PARASEQUENCE INTERPRETATION UNCERTAINTY

We describe four main sources for parasequence mapping and interpretation uncertainty: 1) ambiguities related to selection of parasequence bounding surfaces; 2) ambiguities related to data quality and resolution; 3) ambiguities related to the strata- and surface-based nature of the way a parasequence is defined; 4) ambiguities related to heuristics used during parasequence mapping and interpretation (Fig. 1).

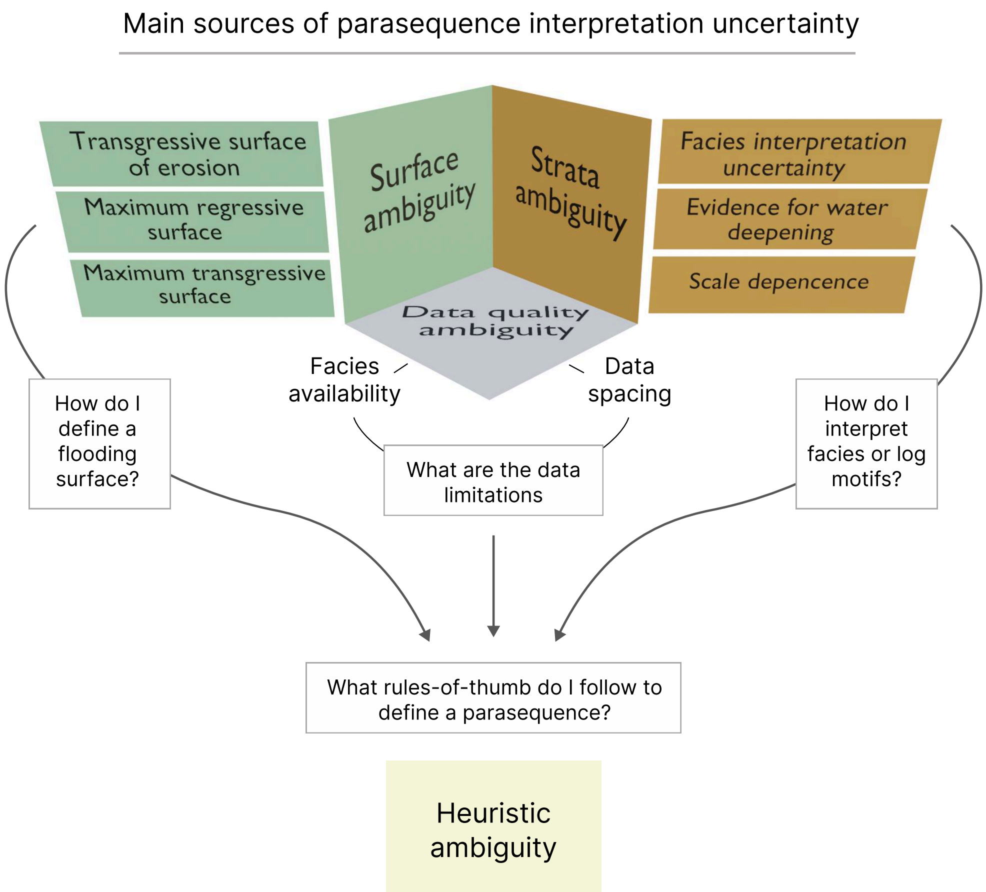

Figure 1. The main sources of uncertainty in parasequence interpretation are related to the choice of sequence stratigraphic surfaces used to represent the flooding surface (surface ambiguity), uncertainties in facies interpretation (strata ambiguity), issues with data quality and spacing (data quality ambiguity), and the rules of thumb used to define a parasequence (heuristic ambiguity).

Ambiguities Related to Bounding Surface Selection

The ambiguity related to the precise placement of parasequence bounding surfaces (flooding surfaces) has been widely discussed in the literature. Refer to Catuneanu (2019) for a more detailed discussion. The main point raised by authors is that a parasequence flooding surface can correspond to several potential sequence stratigraphic surfaces, such as the maximum regressive surface, the transgressive ravinement surface, or the maximum flooding surface. This ambiguity arises from the fact that a single surface must be placed somewhere within what is in actuality a flooding interval and the choice of surface can be time transgressive.

While these points hold theoretical merit, especially when parasequences are considered strictly as sequence stratigraphic units requiring the mapping of distinct surfaces, the issues may be overstated in practical terms. One of the main practical applications of parasequences is predicting fluid flow in the subsurface. Although there may be ambiguity about where to place the flooding surface within an interval, it is the mapping of the lateral extent and thickness distribution of the interval itself that proves most useful for prediction of fluid flow. This is especially relevant when the interval is finer-grained than the underlying succession and forms a distinct flow boundary. In such cases, parasequences are employed to improve the understanding of the three-dimensional distribution of cell properties in a static reservoir model, which can then be used for running flow simulations. Therefore, the ambiguity surrounding the exact placement of the flooding surface may not necessarily translate into ambiguity about the flooding interval itself.

Ambiguities Related to Data Quality and Sampling Resolution

The most intuitive source of parasequence ambiguity stems from the fact that parasequence identification is directly affected by the quality of the data available in an area. Ideally, mapping parasequences should be a facies interpretation-based exercise, where workers are able to objectively assess trends in water depth shallowing and deepening. The lower the quality and quantity of data, the more challenging parasequence mapping becomes (Catuneanu and Zecchin, 2013).

Outcrop case studies that feature numerous parasequences typically come from regions with world-class rock exposures (e.g., Van Wagoner et al., 1990; Garrison and van den Bergh, 2004;

Zhu et al, 2012, Ainsworth et al, 1994, 2015, 2016, 2017; Hampson, 2016; Lin et al., 2019; Pattison, 2019, Howell, this volume). Similarly, subsurface studies from areas with dense well coverage and abundant core tend to define more parasequences (or equivalents) (e.g., Bhattacharya and Walker, 1991, Plint, 2000, Vakarelov and Bhattacharya, 2009). Conversely, areas with sparse well coverage and no core control usually have only a few mapped parasequences, and these are often interpreted with a high degree of uncertainty (Li et al., 2012). In such cases, determining depositional shallowing and deepening trends must rely entirely on log motifs.

From an analogue standpoint, the relationship between data resolution and parasequence mapping should be straightforward. High-quality data case studies should serve as analogues for data-poor areas, potentially offering insights into architectural details that may not be otherwise mappable. Parasequence analogues can be used to fill in depositional gaps where direct observations are limited.

Ambiguities Related to the Dualistic Surface- and Strata-based Definition of Parasequences

Based on their definition, parasequences lay at the intersection between sedimentology and stratigraphy (Swift and Thorne, 1992, Catuneanu and Zecchin, 2013). It is important to note that the parasequence concept includes both surface-based and strata-based aspects. Van Wagoner et al. (1988, 1990) describe a parasequence as a "stratigraphic unit" bounded by "marine-flooding surfaces and their correlative surfaces,". This part of the definition is clearly surface-based and sequence stratigraphical in nature.

In contrast, Van Wagoner et al. (1990) also describes a parasequence in terms of being a "relatively conformable succession" composed of "genetically related beds and bedsets," introducing a sedimentological aspect to its definition. This strata-based, sedimentological aspect is further emphasized by stating that parasequences are "composed of bedsets, beds, laminasets, and laminae," referring to Campbell's (1967) definitions of these terms. The sedimentological aspects of parasequences are also illuminated through the description of their characteristics: flooding surfaces are noted to show "evidence of abrupt increase in water depth," which may be associated with varying degrees of erosion. There is significant discussion regarding the association of such surfaces with transgressive lags. In addition, parasequences are described as exhibiting an "upward shoaling association of facies,", indicating a basinward shift in facies. It is further stated that "parasequence boundaries bound genetically related assemblages of facies, providing an essential framework for facies interpretation and correlation.”

The dualistic surface- and strata-based nature of parasequences contributes to their interpretation uncertainty because mapping them involves a combination of facies interpretation and stratigraphic boundary selection. This inherently makes the process subjective, since factors such as the interpreter’s experience, preferences, and biases influence decisions about what facies criteria constitutes “significant deepening” and where flooding surfaces should be placed. Of special note should be the fact that since parasequences are dependent of facies interpretation, they become subject to depositional environments and stratigraphic architecture uncertainties. As will be discussed later, such aspects become especially problematic since parasequences can be potentially defined at different depositional hierarchy levels even within the same system.

Ambiguities Related to Applying Parasequence Heuristics

While there is a long history of discussion of the merits of parasequences from a theoretical perspective (e.g., Miall, 2010; Catuneanu and Zecchin, 2013, 2020; Catuneanu, 2019), in practice, mapping parasequences is largely a heuristic exercise (Colombera and Mountney, 2020). The interpreter decides whether a shallowing-upward interval occurs on a parasequence scale and whether a fine-grained interval (or a sand-on-sand contact) represents a flooding surface. They also determine which flooding surfaces correlate. Such choices are often also influenced by the practical objective of the mapping exercise and by a prior conception of what a parasequence is.

Figure 2 attempts to summarize the decision-making process commonly used when interpreting parasequences based on facies observations in a shallow marine interval. Interpreting an interval as a parasequence typically begins with identifying grain-size trends, which suggest the presence of a progradational lower portion capped by an interval indicative of transgressive flooding. Evidence of a shallowing-upward trend is often determined based on facies criteria, even though this trend may also be inferred from vertical relationships with the underlying and overlying strata or from wireline log motifs (Posamenter and Allen, 1999).

The presence of a transgressive interval may be interpreted by identifying key surfaces, such as a transgressive ravinement surface, often indicated by a lag deposit, or by recognizing facies evidence that suggests water deepening (Wan Wagoner et al., 1990). In some cases, water deepening is objectively identified, such as when offshore mudstone overlies foreshore strata. In other instances, it is only inferred, such as when a lower delta front sandstone is overlain by finer grained prodelta deposits. The pink cells in Figure 2 highlight steps in the interpretation process where the presence of parasequences is based on inferred criteria, such as water shallowing trends, water deepening trends, and the identification of key surfaces.

The heuristics shown in Figure 2 are, of course, an oversimplification, and additional decision steps are often made based on local factors. The objective interpretation of parasequences can be significantly improved by being able to walk out key intervals and surfaces in outcrop, allowing direct observation of their lateral extents. Parasequence interpretation can become highly uncertain when working with low-resolution subsurface data, especially when large well spacing and limited or no core availability are involved. In such cases, correlation and identification of flooding surfaces may rely heavily on guesswork or bias and be driven by pre-existing models.

MECHANISMS THAT CAN RESULT IN FORMATION OF FACIES SUCCESSIONS THAT CAN RESEMBLE PARASEQUENCES

It is important to consider the different mechanisms that can generate parasequence-like successions in a shallow marine setting and to place them within a depositional hierarchy framework. This allows direct comparisons based on types between parasequences deposited in different areas.

Figure 3 outlines several mechanisms that can generate successions that resemble parasequences which occur on three distinct depositional hierarchical levels (see Vakarelov and Ainsworth, 2013). All mechanisms can produce laterally correlatable fine-grained intervals that cap a coarsening-upward deposit. However, only the first mechanism is associated with a significant deepening tied to a flooding interval and thus meets the original definition of a parasequence (Van Wagoner et al, 1990).

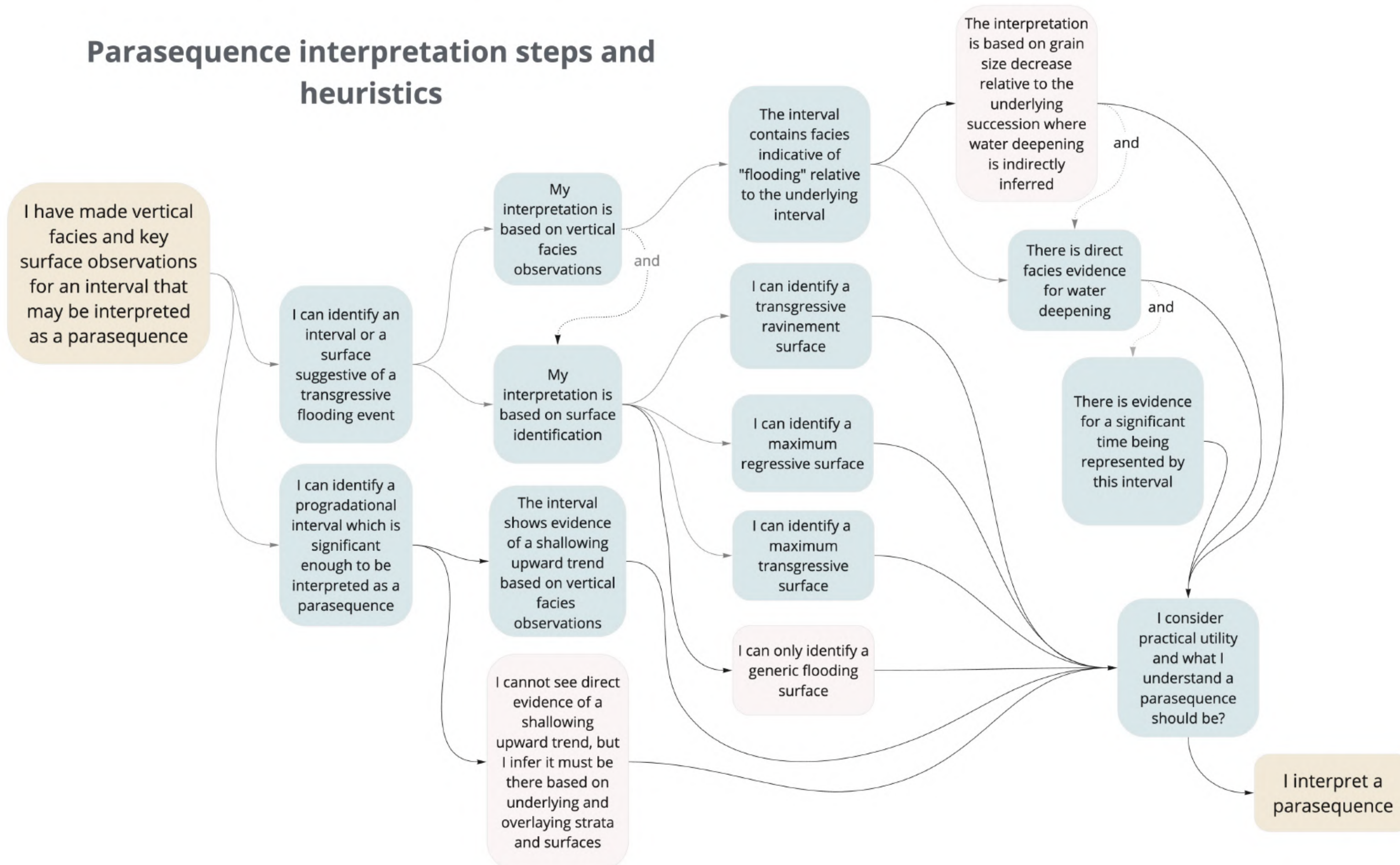

Figure 2. Typical decision-making steps and heuristics used when interpreting a parasequence based on facies core and outcrop data. The steps shown with a red background often results in identification of parasequences that may be formed by both inter-depositional system allogenic and intra-depositional system autogenic mechanisms (see text for details).

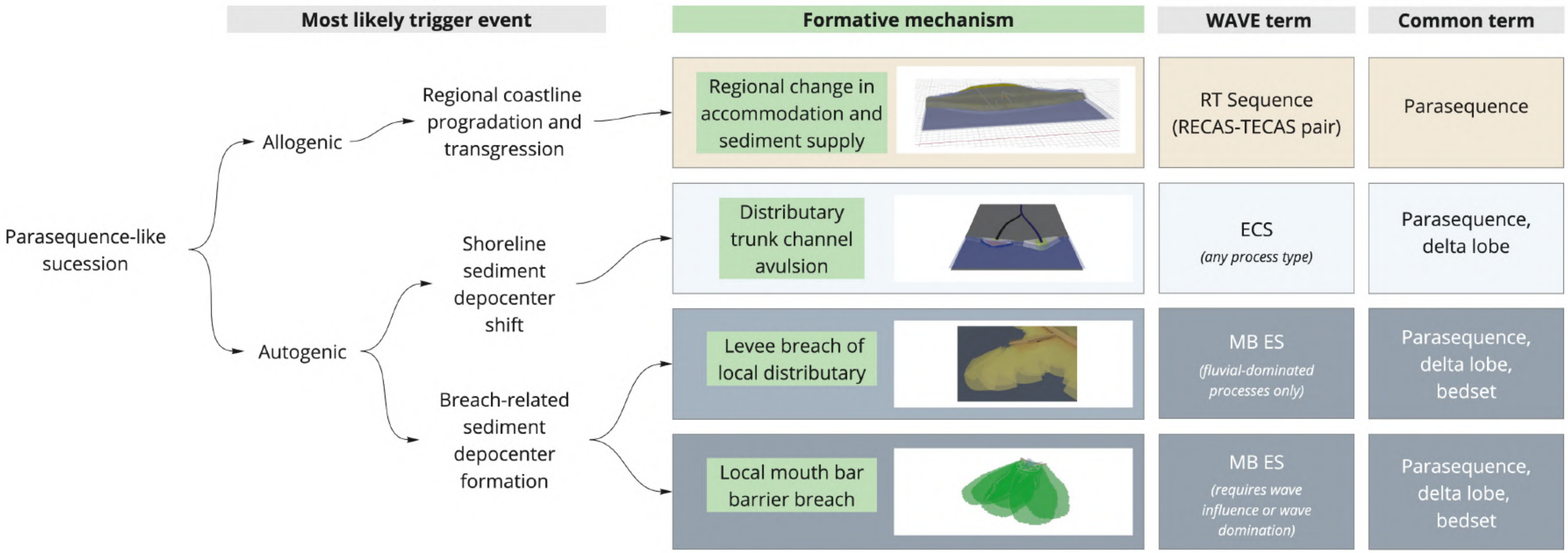

Figure 3. Various regional allogenic and subregional to local autogenic formative mechanisms that can generate parasequence-like successions, showing the event, responsible mechanism, *WAVE* Process and Architectural Classification term, as well as common terminology used for such successions.

Mechanism 1) Regional Coastline Progradation and Transgression Caused by Major Allogenic Changes in Rates of Accommodation and Sediment Supply

This is the most widely accepted mechanism for parasequence formation and is the basis for the initial parasequence concept (Van Wagoner et al., 1990, Posamentier and Allen, 1999, Catuneanu, 2006). Shallowing-upward and subsequent flooding intervals occur in response to major allogenic changes in rates of sediment supply and accommodation, which result in regional-scale regressions and transgressions. 'Regional' in this case refers to, at a minimum, the entire lateral extent of the depositional system along the coastline. These changes are typically driven by climate variations, leading to fluctuations in rates of precipitation and sediment supply, as well as changes in relative sea level, in turn driven by both eustatic and tectonic controls (Catuneanu, 2006, Miall, 2010).

Formation of shallowing-upward intervals at any one location happens in responses to regional seaward migrations of the coastline, occurring when the rate of sediment supply exceeds the rate of accommodation creation (Posamentier and Allen, 1999) (Fig. 4). Flooding intervals form when the rate of accommodation creation outpaces the rate of sediment supply.

Parasequence formation under these conditions is independent of the processes and architecture of internal depositional systems. It can be said to occur on an inter-depositional system scale. The same parasequence can contain a range of internal environments which can change along both depositional dip and depositional strike directions (see RECAS vs. ECA discussion in Vakarelov and Ainsworth, 2013). The parasequence will be mapped based on identification of key bounding surfaces that can be correlated laterally, even as the depositional character of internal facies successions changes. The same flooding surface can bind a wave-dominated interval and a fluvial-dominated interval which formed within the same regional pulse of coastline migration (i.e. they are part of the same parasequence).

Numerous researchers limit interpretations of parasequences to these types of regional-scale deposits (Wan Wagoner et al, 1990; Hampson et al, 2008, Charvin et al., 2010, Ainsworth et al., 2017, 2018, 2020). This approach also aligns with how parasequences are typically mapped in wave-dominated shoreface systems, where the concept was first developed (Van Wagoner et al., 1990). Hampson et al. (2008) discussed three architectural levels in wave-dominated systems,

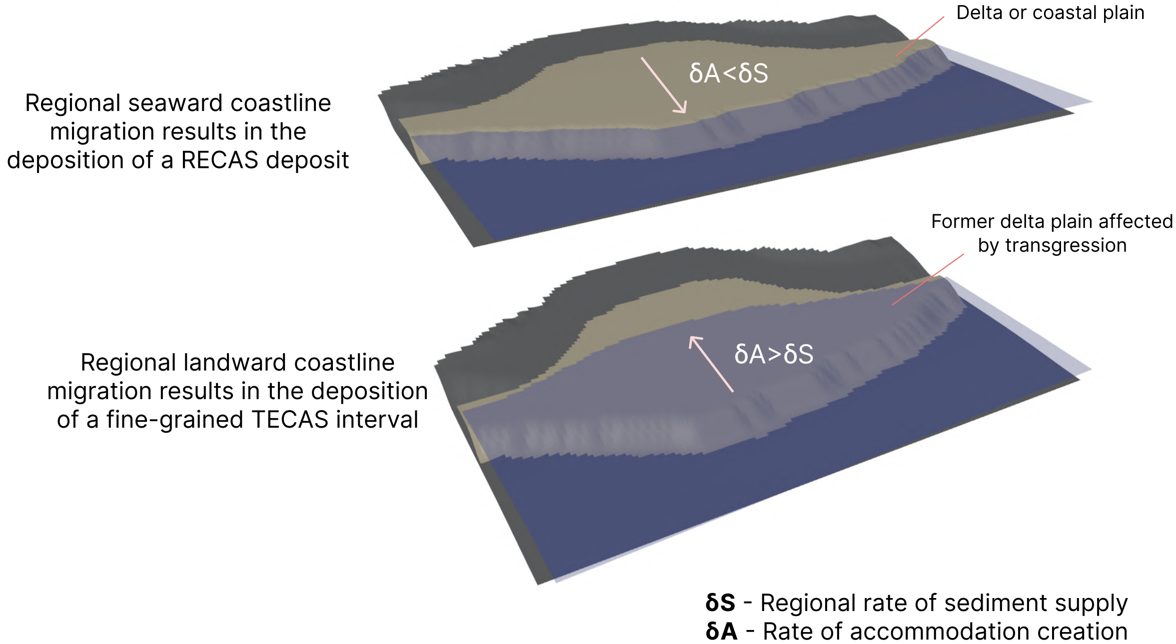

Figure 4. Formation of a parasequence driven by regional variations in the rate of sediment supply (S) and the rate of accommodation creation (A). (Top) A regional pulse of seaward coastline migration occurs when the rate of sediment supply exceeds the rate of accommodation creation, resulting in the formation of a Regressive Element Complex Assemblage Set (RECAS) interval. (Bottom) A regional pulse of landward coastline migration follows when the rate of accommodation creation exceeds the rate of sediment supply, forming a Transgressive Element Complex Assemblage Set (TECAS) unit. Together, the RECAS-TECAS pair forms an RT Sequence (i.e., a parasequence).

with the highest level, the progradational wave-dominated shoreline system, corresponding to a parasequence. The two lower levels, beach ridges and beach ridge sets, were described as representing intra-parasequence architecture. This was also the approach followed by Ainsworth et al. (2020) who compiled a database of parasequences limited to "regressive–transgressive full or partial shelf transits." Constraining the parasequence definition in this way enabled cross-comparison of parasequences from different studies, allowing for the establishment of useful relationships that predict their thickness and progradational extent.

This type of parasequence can be effectively described using the *WAVE* Process and Architectural Classification presented in Vakarelov and Ainsworth (2013), which uses maximum regressive and maximum transgressive bounding surfaces. The progradational portion of the parasequence is referred to as a RECAS unit (Regressive Element Complex Assemblage Set), encompassing all deposits associated with the regional seaward migration of the shoreline. The RECAS unit is bounded by a maximum transgressive surface at its base and a maximum regressive surface at its top. The flooding interval, in turn, is described as a TECAS unit (Transgressive Element Complex Assemblage Set), which has the maximum regressive surface at its base and the maximum transgressive surface at its top. The entire parasequence can be thought of as an RT Sequence, which is made up of a pair of RECAS and TECAS deposits (see definition in RT Sequence in Ainsworth et al, 2017).

The key advantage of this nomenclature lies in its parent-child hierarchical nature, which allows for straightforward handling of different architectural scales. Referring to a unit as RT Sequence clearly communicates that we are describing both the regressive and transgressive portion of a parasequence. Use of the RECAS term, on the other hand, conveys that we are only addressing its shallowing upward portion of a parasequence. Importantly, both the RT Sequence and RECAS units clearly refer to regional-scale deposits, which are independent of the specific depositional system characteristics that shape their internal architecture.

Mechanism 2) Trunk Distributary Channel Avulsion-driven Sediment Point Source Switching at the Coastline

The term ‘parasequence’ becomes more problematic when used to describe autogenic deposits, such as avulsing delta lobes, which can also form vertical facies successions that resemble parasequences (Charvin et al, 2010; Miall, 2010; Hampson, 2016; Ainsworth et al., 2017). In an avulsion event, the upstream shift of a trunk distributary triggers a significant reorganization at the shoreline (Slingerland and Smith, 2004; Stouthamer and Berendsen, 2007). In its simplest form (full avulsion), such an event will result in the formation of a new sediment point source depocenter in one location and the full abandonment of the previously active depocenter at another location (Slingerland and Smith, 2004).

The formation of the new depocenter leads to the rapid accumulation of sediments on top of former mud-prone seafloor deposits (Fig. 5). This progradational process can cause the shoreline to advance significantly seaward, resulting in the deposition of a parasequence-like, vertically shallowing-upward sedimentary body (Fig. 5).

An abandoned depocenter will also be significantly impacted by an avulsion, as the loss of rate of fluvial sediment supply shifts the balance between deposition and erosion. Waves and tides often partially erode these deposits, creating a local ravinement surface and triggering local shoreline transgression (Fig. 5). This erosion can potentially result in the formation of a lag deposit (Fig. 5). While such a lag deposit may resemble a transgressive lag formed by regional transgression, its extent will be limited to the shallow portion of the former depocenter.

After the local landward shoreline retreat is complete, the abandoned depocenter will often continue to receive fine-grained sediment from alongshore sources. Shallow marine systems are highly efficient at transporting mud along shore which often accumulates well beyond the lateral extent of the subaerial expression of a delta lobe (e.g., Cattaneo et al, 2003; Neill and Allison, 2005; Frascari et al., 2006). These fine-grained deposits, which have high-preservation potential below the depth of depocenter wave ravinement, will form a clinoforming interval that caps the most distal surface of the former depocenter (Fig. 5). In terms of vertical facies stacking, this fine-grained deposit will resemble a flooding interval, overlaying the coarsening-upward succession formed during the active progradation of the depocenter.

Above the depth of depocenter ravinement, alongshore-sourced fine-grained strata may have poor preservation potential unless the rate of deltaic background subsidence is sufficiently high and the frequency of avulsions in the system is sufficiently low. As a result, in theory, a progradational, shallowing-upward succession can be capped by a variety of deposits, including a fine-grained interval, a lag deposit, or a lag deposit overlain by fine-grained strata (Fig. 5). The

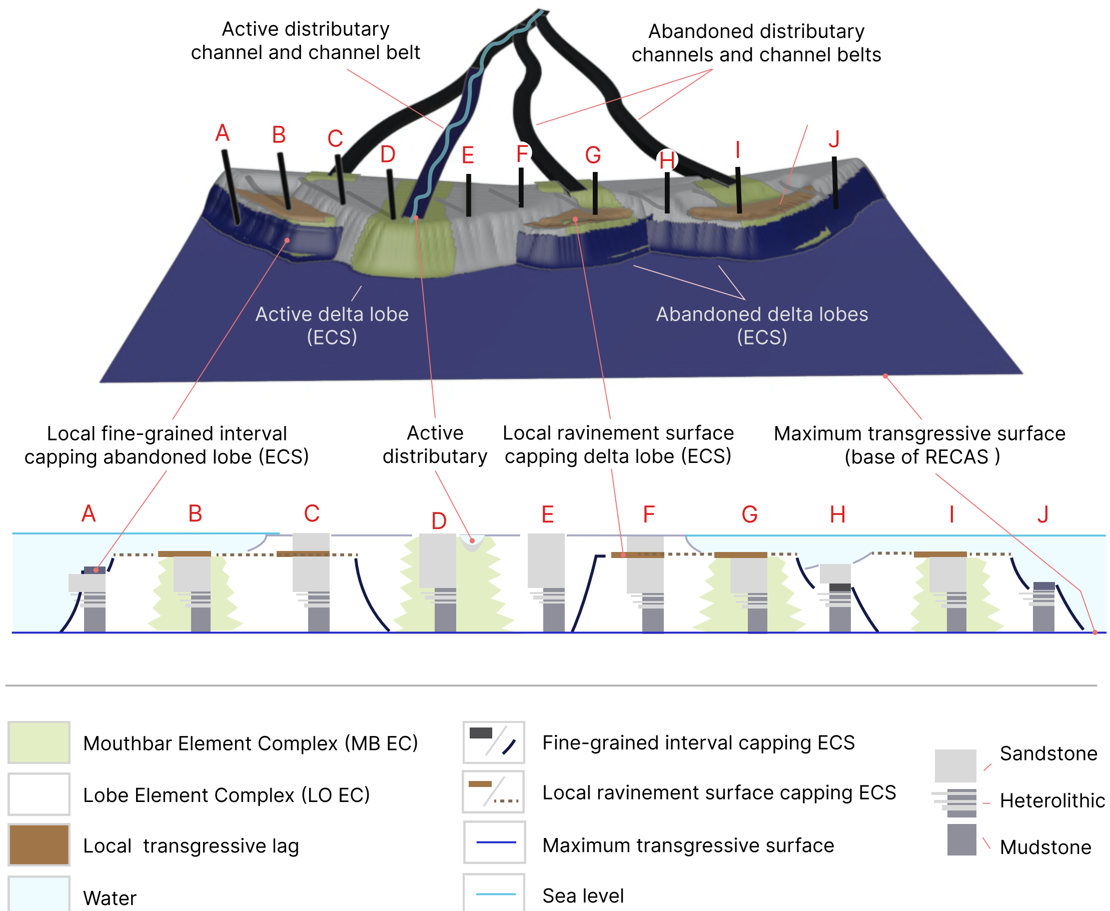

Figure 5. Formation of parasequence-like successions by autogenic distributary trunk channel avulsions. 3D view: Avulsion events result in the formation of three abandoned delta lobes (ECS) and one active delta lobe (ECS). Each abandoned ECS unit has been partially eroded by local wave ravinement, which can potentially resemble regional transgressive wave ravinement surfaces in facies expression. Cross section: An idealized cross-section through wells A to J, showing a strike view through stratigraphy containing an abandoned ECS units and part of the active ECS unit. Note that a fine-grained interval that can potentially be interpreted as containing a flooding surface will be best expressed along clinoform surfaces.

specific nature of the capping deposits will depend on local subsidence rates and avulsion dynamics.

A regional progradation of a coastline will typically encompass numerous avulsion-related deposits. These deposits will be shaped by the ongoing interplay between the formation of new depocenters and the abandonment and erosion of older ones. Lag deposits and fine-grained strata capping abandoned depocenters will often be vertically overlain by sediments from younger depocenters. The degree of vertical stacking versus offlapping relationships between depocenters at the same location will depend on accommodation space and sediment supply conditions (Ainsworth et al., 2017). High accommodation conditions may promote more vertical stacking, while limited accommodation may favor offlapping, with newer deposits prograding seaward rather than building on top of older deposits.

The avulsion-related parasequence-like depocenters described in this section are categorized as Element Complex Set (ECS) deposits according to the *WAVE* Process and Architectural Classification (Vakarelov and Ainsworth, 2013, Ainsworth et al., 2017). The advantage of using this nomenclature, rather than generic terms like delta lobe or sediment depocenter, is that it eliminates confusion regarding the architectural scale of the deposit.

Referring to these deposits as ECS units rather than parasequences clarifies both the formative mechanism as well as the depositional hierarchy of the described interval.

Danube example: The Danube delta shows well-defined delta lobes (ECS) that have formed since the Holocene highstand (Giosan et al, 2005; Panin et al, 2016). Figure 6a shows an interpreted satellite map with labelled geomorphological features. The barrier island / spit feature labelled on the map was a transgressive feature which separated a large bay behind it (Danube Gulf) from the open sea in front (Panin et al, 2016). The large marine bay was similar to other unfilled bays currently observable in nearby systems. A change in the rate of accommodation development relative to the rate of sediment supply ($\delta A/\delta S$) regime after stabilization of sea level resulted in the gradual infilling of the bay and the regional seaward migration of the coastline from initially behind to then in front of the former barrier where deposition became influenced by waves. All regressive deposits both landward and seaward from the barrier belong to a single RECAS interval (Fig. 6a).

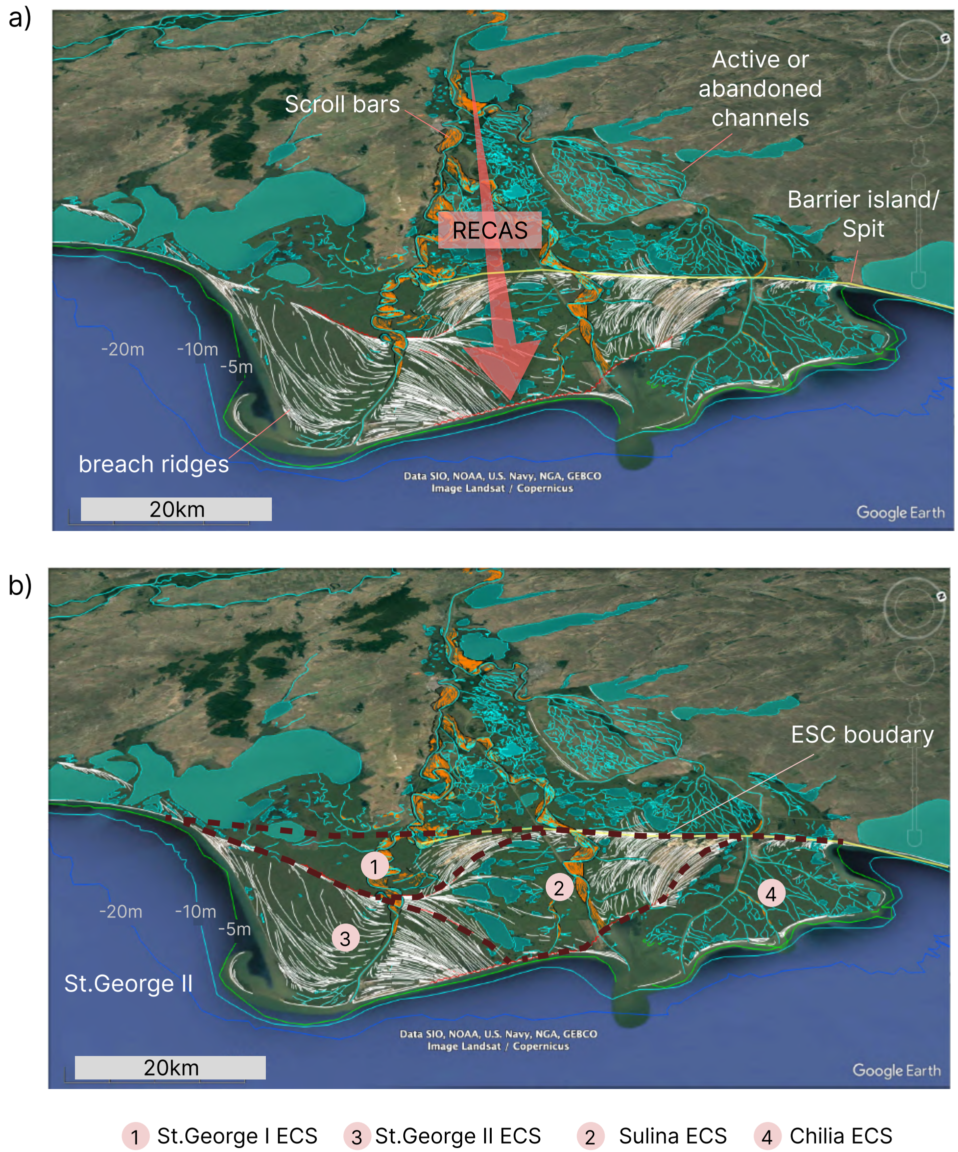

Figure 6. Interpreted geomorphological map showing large-scale architectural units in the Danube Delta, Romania. a) Stabilization of sea level during the Holocene resulted in a regional pulse of seaward coastline migration, forming an extensive Regressive Element Complex Assemblage Set (RECAS) deposit. This RECAS deposit includes a portion accumulated in a large bay landward of a barrier/spit and a portion that prograded seaward of this feature. b) Interpreted Element Complex Set (ECS) units seaward of the barrier, associated with regional trunk channel avulsion events. ECS units at this scale can form parasequence-like successions, but we do not recommend labeling such units as parasequences.

Regional avulsions of Danube trunk distributaries result in formation of four well-defined delta lobes (Element Complex Sets, ECS) (Fig. 6b). Two of the lobes, the southern St.George II to and the northern Chilia are currently active and still prograding (Giosan et al, 2005; Panin et al, 2016). The other two lobes, St.George I and Sulina, have been abandoned and partially ravined and removed by waves. The Sulina lobe shoreline has locally been transgressed for over 10 - 15km after lobe abandonment (Panin et al, 2016), which is also visible by the bathymetric contours visible in Figure 6b.

Mechanism 3) Channel levee or barrier breach events resulting in local depocenter formation

Parasequence-like deposits consisting of shallowing upward successions capped by mudstones that can resemble flooding intervals can also be formed by autogenic processes operating on much smaller and higher-frequency relative scales than the trunk distributary avulsion mechanism discussed above. The formation of such successions is linked to the presence of a depositional element that initially constrains flow and is later breached. Depending on local depositional conditions, this breached element can be (i) the levee of a distributary channel or (ii) a small wave-generated barrier or spit that forms in front of a river mouth during periods of low riverine discharge. The breaching event is typically triggered by a flood event and followed by a rapid pulse of deposition and localized progradation, forming a new sediment depocenter. Like trunk channel avulsion deposits (ECS), the creation of the new depocenter is often accompanied by the abandonment of the former depocenter.

In practice, such breach-related depositional units will only be interpreted as potential parasequences if they are prominent enough to be considered to occur on parasequence scale by a practitioner (see Fig. 2). Additionally, conditions must allow for at least partial vertical stacking of successive depocenters, accompanied by deposition of intermittent fine-grained intervals or formation of key contacts that can be interpreted as containing flooding surfaces.

Depocenters will have the following characteristics: 1) They will occur on a local scale and will have minimal impact on regional coastline evolution; 2) They will form at high temporal frequencies, often over periods of months to years; 3) The formation of such deposits will occur under specific depositional process conditions, making them closely tied to the properties of their parent depositional systems.

Such deposits and their hierarchical relationships to parent units can be effectively described using the *WAVE* Process and Architectural Classification: The individual depocenters will be labeled as Mouthbar Element Sets (MB ES). A group of MB ES units, supplied by the same trunk distributary, will form a Mouthbar Element Complex (MB EC), which in turn will be a subset of a parent Element Complex Set (ECS) unit (see parent-child relationships in Figure 7).

We describe two types of MB ES deposits which are sufficiently different to be treated separately. One occurs under fluvial-dominated conditions and the other requires the presence of waves, reflecting the strong influence of local depositional conditions for the formation of such units.

3a) Distributary Channel Levee Breach.-

A mechanism that can result in the deposition of parasequence-like successions is the breach of distributary channel levees, particularly when the levees are immediately adjacent to standing bodies of water (e.g., interdistributary bays) (Fig. 8). Such deposits typically initiate during a river flood, causing a levee breach and triggering rapid accumulation of a new depocenter (Mouthbar Element Set, MB ES) (Fig. 8). Where more than one levee breach node occurs along a common channel branch (Fig. 9), the MB ES deposits can be grouped in a parent Element Set Cluster (ES Cluster) unit (see also Ainsworth and Vakarelov, this volume). New levee breaching events often lead to the abandonment of old distributary channel stretches, which can occur on both MB ES and MB ES Cluster scale, resulting in the cessation of sediment supply to their associated mouth bar and delta front deposits.

Under the right depositional conditions, the levee breach mechanism can form units that may be interpreted as parasequences (Fig. 8b, 9b). Depending on local bathymetry, such progradational units can range from meters to tens of meters in thickness, with their internal facies often displaying a clear shallowing-upward trend. These progradational intervals are frequently abandoned and draped by fine-grained strata sourced from nearby active depocenters.

What are the required depositional conditions for the formation of such intervals? A survey of global modern depositional systems suggests that this style of deposition is associated with digitate fluvial-dominated systems (F) that prograde in water depths of over several meters.

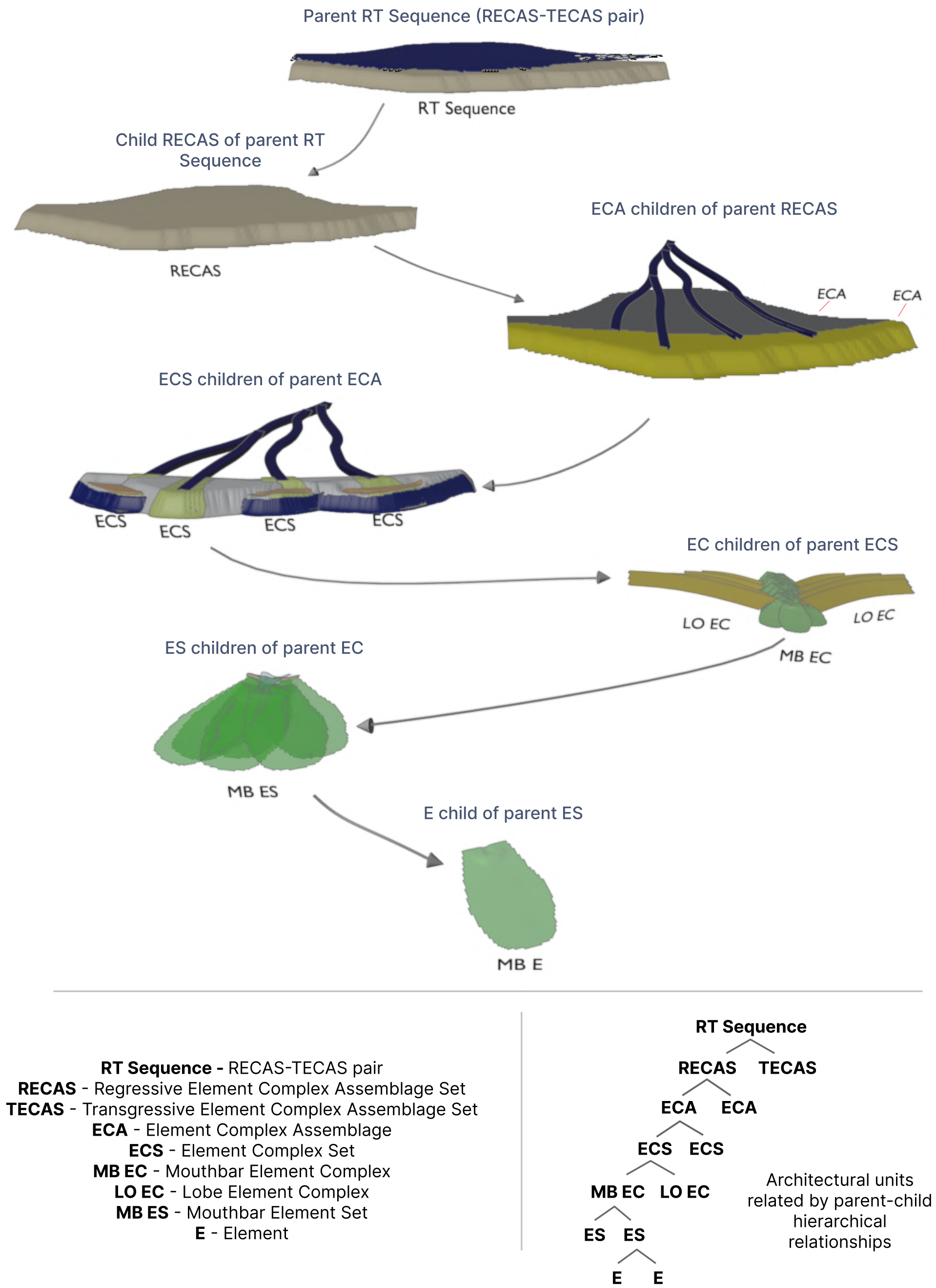

Figure 7. Hierarchical relationships between architectural units in the *WAVE* Process and Architecture classification (Vakarelov and Ainsworth, 2013). The units on the left (RECAS, ECS, and ES) are typically bounded by clearly identifiable surfaces which can be capped by fine-grained strata and can form parasequence-like successions. The units on the right (ECA and EC), which are based on internal stratal characteristics, often have transitional boundaries and would not typically by themselves from parasequence-like successions.

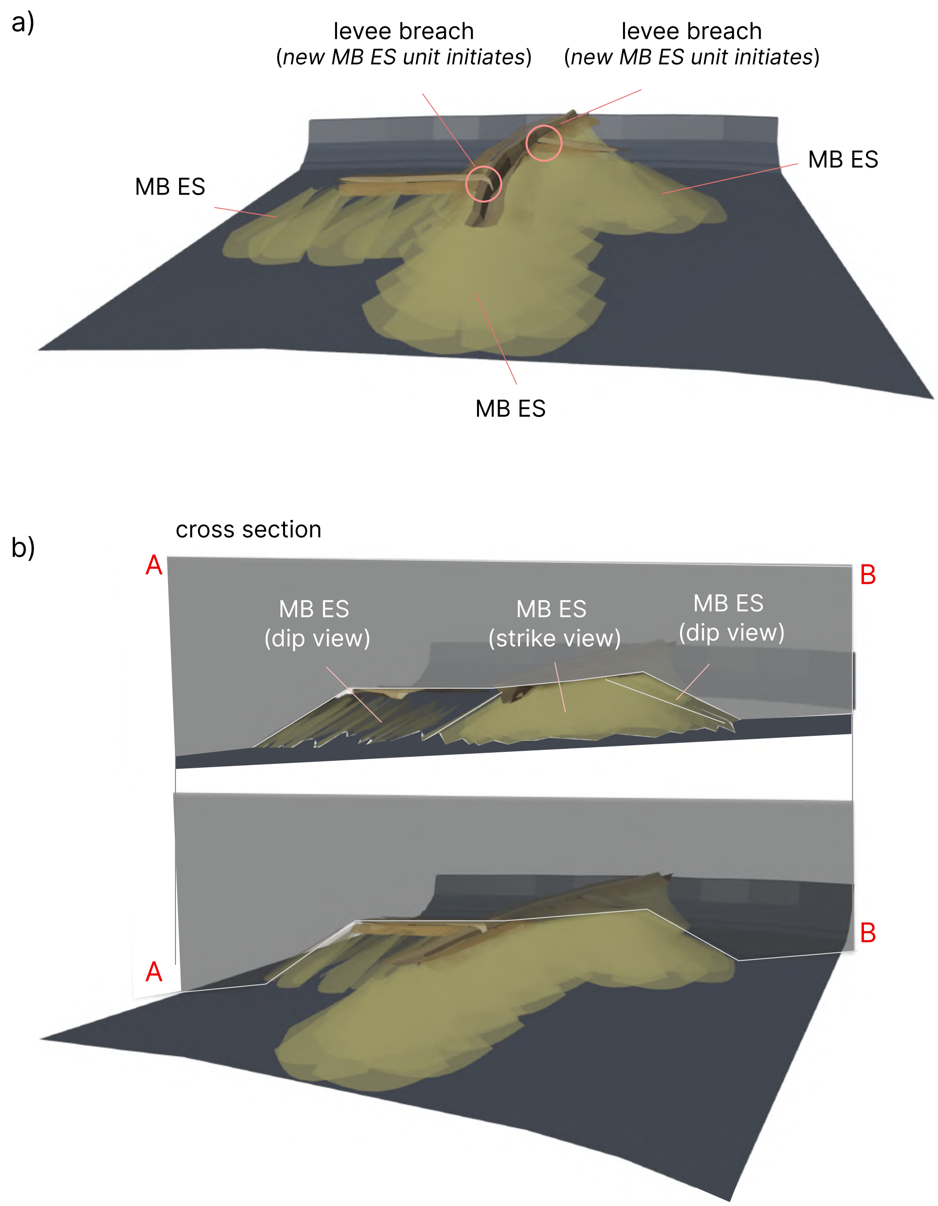

Figure 8. Formation of Mouthbar Element Sets (MB ES) by levee breach in digitate, fluvial-dominated deltaic systems. a) A 3D conceptual model showing three MB ES units. A new levee breach often leads to the abandonment of an older MB ES deposit (not shown). b) A cross-section through the same deposits, viewed from a different angle, illustrating the expression of the three units. Adjacent units display different local dip and strike orientations. Such intervals can potentially be interpreted as parasequence-like successions when they occur on a sufficient scale and are capped by well-developed fine-grained flooding intervals.

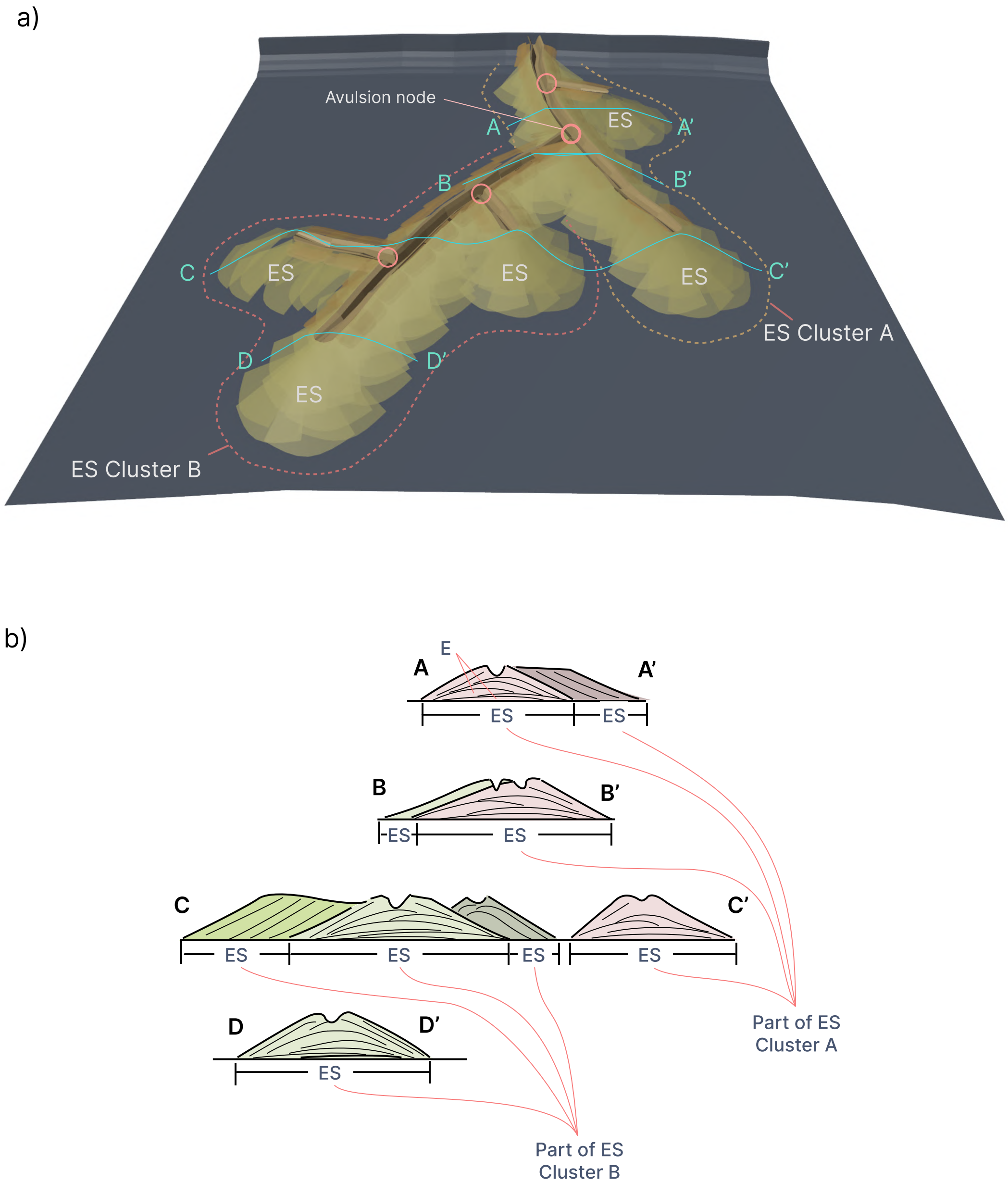

Figure 9. Formation of Mouthbar Element Set Cluster (MB ES Cluster) units by genetically related Mouthbar Element Set (MB ES) units linked via common channel branches. This is an often-encountered depositional pattern in digitate, fluvial-dominated deltaic systems. a) A 3D conceptual model showing two MB ES Cluster units. Note that a formation of a new MB ES Cluster often leads to the abandonment of an older MB ES Cluster which is not shown in the diagram. b) Schematic cross sections of strata geometries expected in different portions of the MB ES Clusters and their internal MB ES deposits.

While waves and tides may operate in the background, they will tend to be strongly subordinate to the fluvial process and will not be capable of moving significant quantities of sediment during active progradation.

Caño Matunilla delta example: The formation of an interval dominated by MB ES deposits formed by levee breach is illustrated in Figure 10. The rapid progradation of the Caño Matunilla delta, Colombia, is characterized by the formation of digitate, fluvial-dominated deposits (MB ES) with well-established distributary channels and levees. Individual MB ES deposits are of sufficient size (i.e., thickness) to form parasequence-like successions. The delta, which is made up of many MB ES deposits, some of which can be grouped into MB ES Clusters (not shown on map), has prograded for over 4 km in both dip and strike directions between 1987 and 2022. The entire delta represents several decades of progradation and occurs on a scale of a laterally extensive outcrop.

Dip and strike-oriented progradation of the system almost entirely occurs via levee breach events that initiate new MB ES growth episodes. Former MB ES and MB ES Cluster intervals are gradually abandoned after a newly formed channel picks up most of the fluvial discharge. Numerous levee breach events result in a rather complicated delta plan-view architecture formed by a number of MB ES intervals with various orientations. Progradation of individual MB ES units and, thus internal and bounding clinoforms, occurs in regional seaward, alongshore, and even landward directions. Available bathymetric data suggests that MB ES units have a maximum thickness of about 10 m and that clinoforms dip in both depositional dip-oriented and depositional strike-oriented senses relative to the orientation of the local feeder channel.

3b) Mouthbar Barrier Breach.-

Another mechanism that can likely result in the deposition of local parasequence-like successions involves the interaction between fluvial and wave processes at a distributary channel mouth. Like the levee-breach mechanism discussed earlier, the formation of these deposits is influenced by the river's flow stage.

During normal river flow stages, wave energy in such intervals is sufficient to form barrier-like or spit sediment bodies that can divert the channel flow behind them (Fig. 11). The sediment forming these wave-generated deposits may originate directly from the channel mouth-bar area

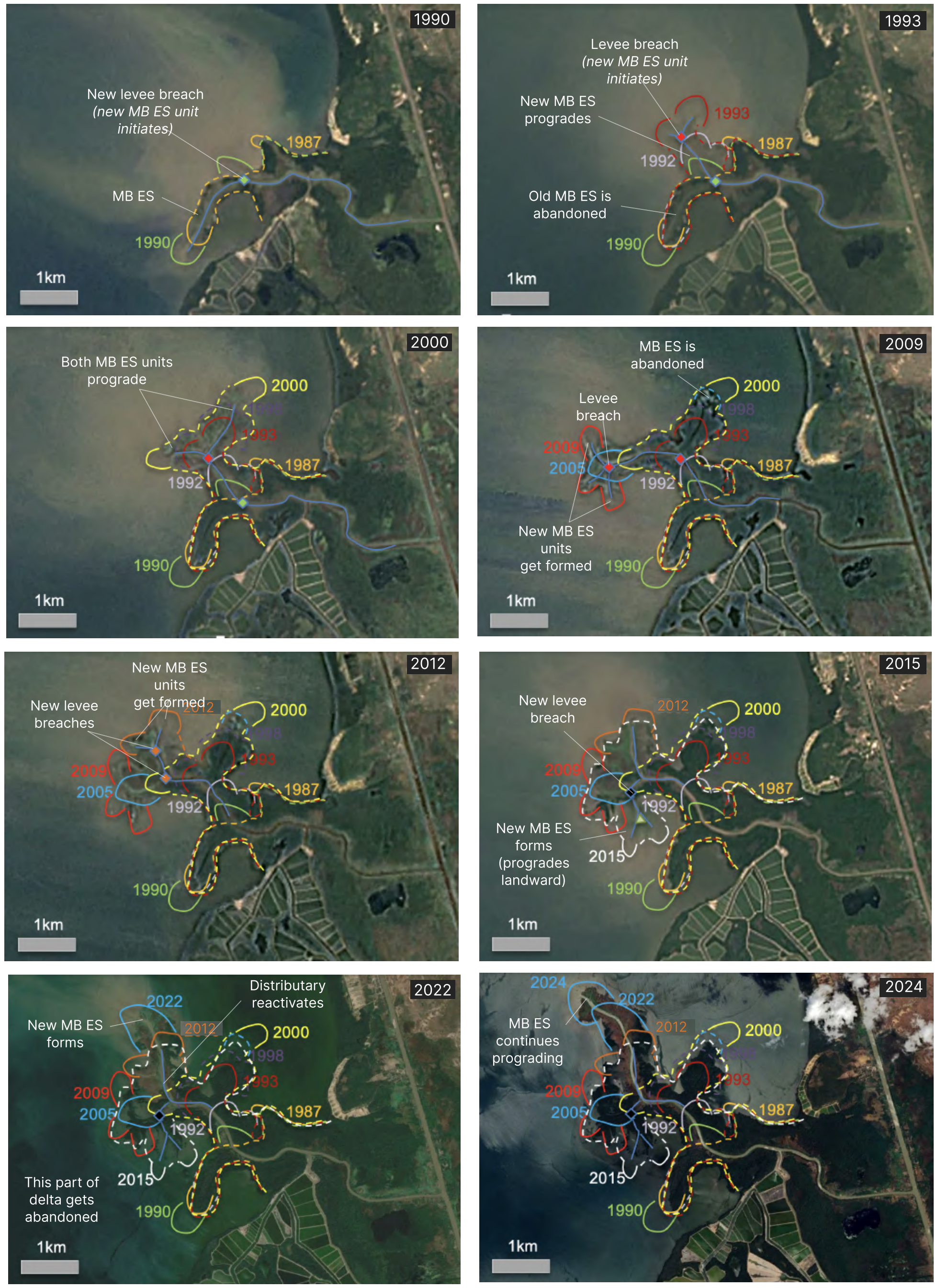

Figure 10. Rapid progradation of the Caño Matunilla delta, Colombia, between 1987 and 2024 in approximately 10 meters of water depth. This digitate, fluvial-dominated system is built by MB ES deposits formed through multiple episodes of distributary channel levee breaches. The units prograde in various directions, creating an interval with complex 3D architecture. The MB ES outlines on the map represent only their subaerial expression, with the true extent of the units extending farther below sea level, forming clinoforms.

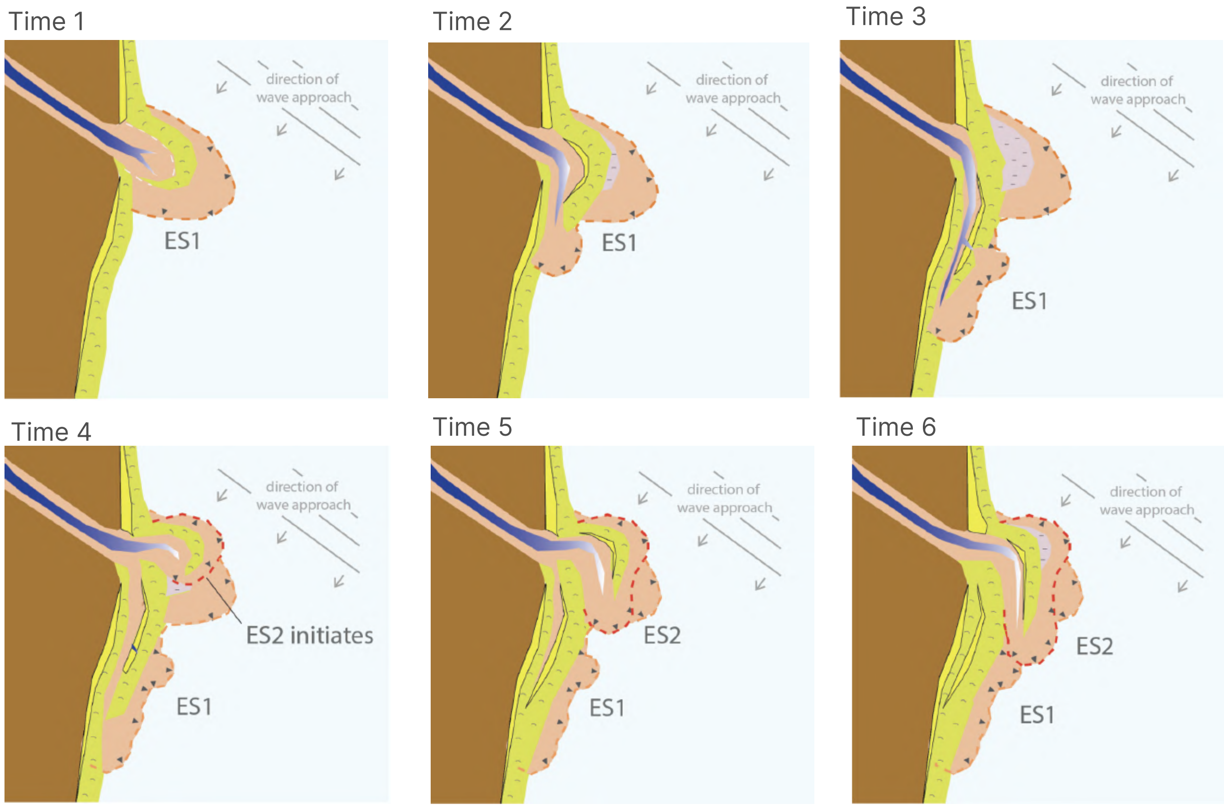

Figure 11. A 2D conceptual model showing the formation of MB ES units (labeled as ES1 and ES2) through a barrier/spit breach mechanism, which requires the presence of waves. Time 1–Time 3: An MB ES body initially forms in front of the channel mouth. Fairweather waves rework the sediment, building a spit that diverts the channel and its mouth bar deposits along the shore. Time 4–Time 6: The wave-generated feature is breached, initiating the deposition of a new MB ES depocenter.

or can be from an updrift, alongshore sediment source. A river flood event will breach the barrier and form a new sediment depocenter (MB ES), which will often lead to the abandonment of the previous depocenter. These processes will repeat, resulting in cycles of barrier breaches, progradation of new MB ES units, and the abandonment of previously active MB ES units.

This style of deposition will result in the formation of numerous MB ES units which can potentially form successions that resemble parasequences (Fig. 12). Individual MB ES units will be progradational in nature and will contain internal shallowing-upward facies trends. An abandoned MB ES will typically be located near an active channel, making it likely a site for river-sourced mud deposition below fairweather wave base. This can lead to the formation of fine-grained intervals that will resemble prodelta deposits (i.e., flooding intervals), which can in turn be overlain by younger MB ES units.

A parasequence-like succession interpretation of such MB ES units will only be possible if: (i) The units occur on a sufficient scale for an interpreter to consider them as potential parasequences (see Fig. 2); (ii) The units are capped by fine-grained intervals that can be interpreted as containing potential flooding surfaces. These conditions will be met in systems capable of delivering sufficient sediment to a channel mouth at a shoreline with a progradational water depth that is significant enough for meaningful vertical scaling of MB ES units, while not great enough to impede progradation.

Mangoky delta example: The formation of several barrier breach-type MB ES depocenters has driven rapid progradation of the Mangoky Delta in Madagascar (Fig. 13). Between 1984 and 2023 (39 years), the delta has prograded for 4 km in the depositional dip direction (circa 100 m per year) and for 10 km in strike direction. Limited historic Landsat data (not shown) suggests that rapid subaerial progradation had not begun by 1973, which was a time prior to an avulsion event that formed a new sediment depocenter in this portion of the coastline. The precise date of the avulsion is not known. .

Present-day deposits are accumulating in water depths of 10 - 12 meters, based on available bathymetric data, which serves as a proxy for the vertical thickness of the prograding shallowing-upward intervals. The architectural style of the system is driven by the delivery of fluvial-sourced sediment to the shoreline, leading to rapid mouthbar depocenter (MB ES)

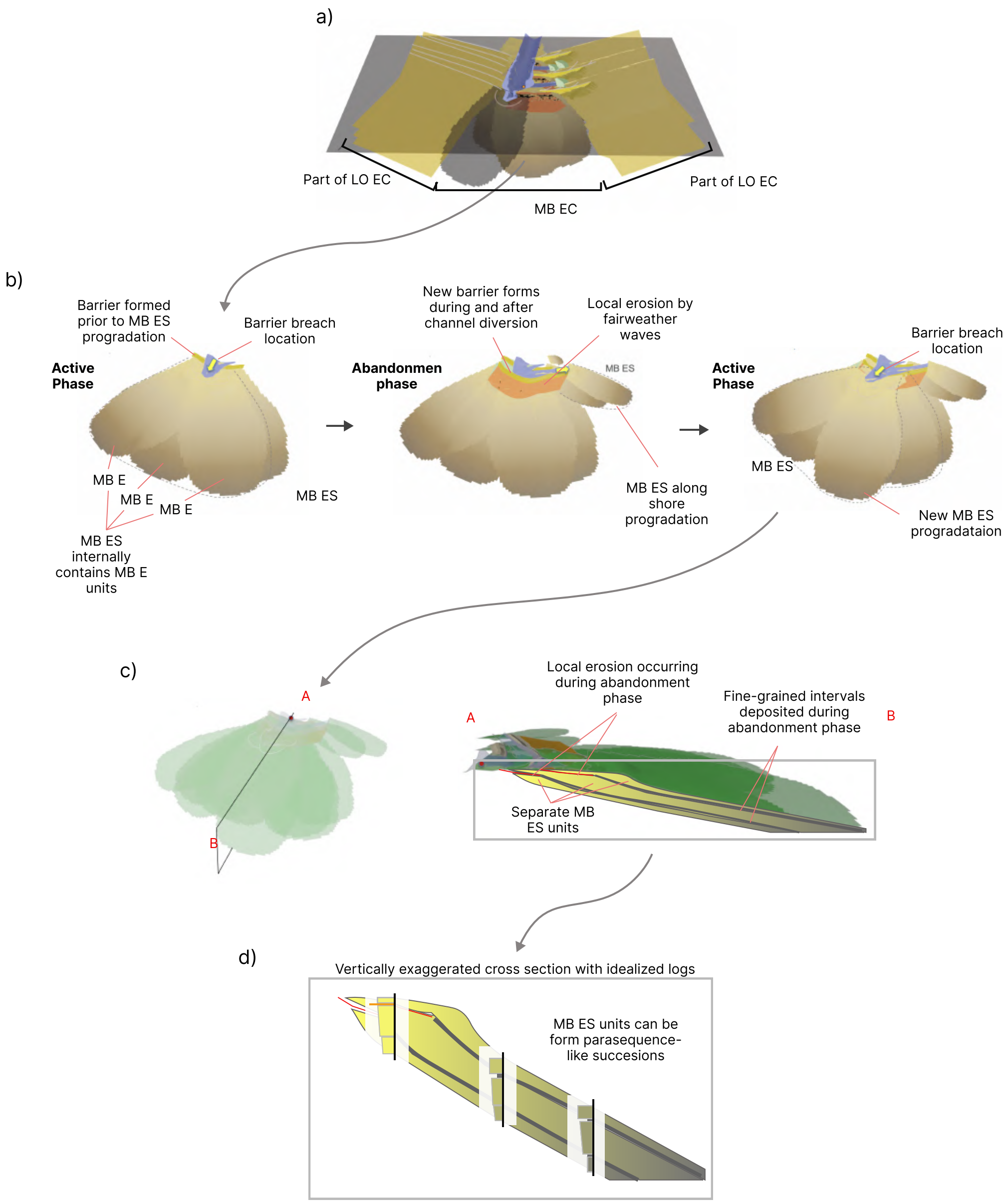

Figure 12. A 3D conceptual model illustrating the accumulation of separate MB ES deposits in front of a river mouth through a barrier breach mechanism. a) Deposition of MB ES units occurs as part of a parent Mouthbar Element Complex (MB EC), which includes mouth bar and delta front deposits sourced directly from the river, adjacent to Lobe Element Complex (LO EC) deposits accumulating along strike. b) The mouth bar area in front of the channel mouth is often partially reworked by waves, forming a barrier-like deposit that can be breached during riverine floods. A breach event creates a new MB ES depocenter (active phase). The upper portion of this new MB ES depocenter is subsequently reworked by waves, forming a new barrier-like feature, shifting sedimentation to an adjacent area (abandonment phase). The process repeats with each breach event, initiating new MB ES depocenters. c) A cross-section through this stratigraphy shows vertical stacking of MB ES units within the parent MB EC, typically capped by fine-grained strata deposited during abandonment phases. d) A vertically exaggerated, dip-oriented cross-section through the same stratigraphy shows the idealized expression of these units in core or outcrop. If sufficiently scaled, these units can be interpreted as parasequence-like successions.

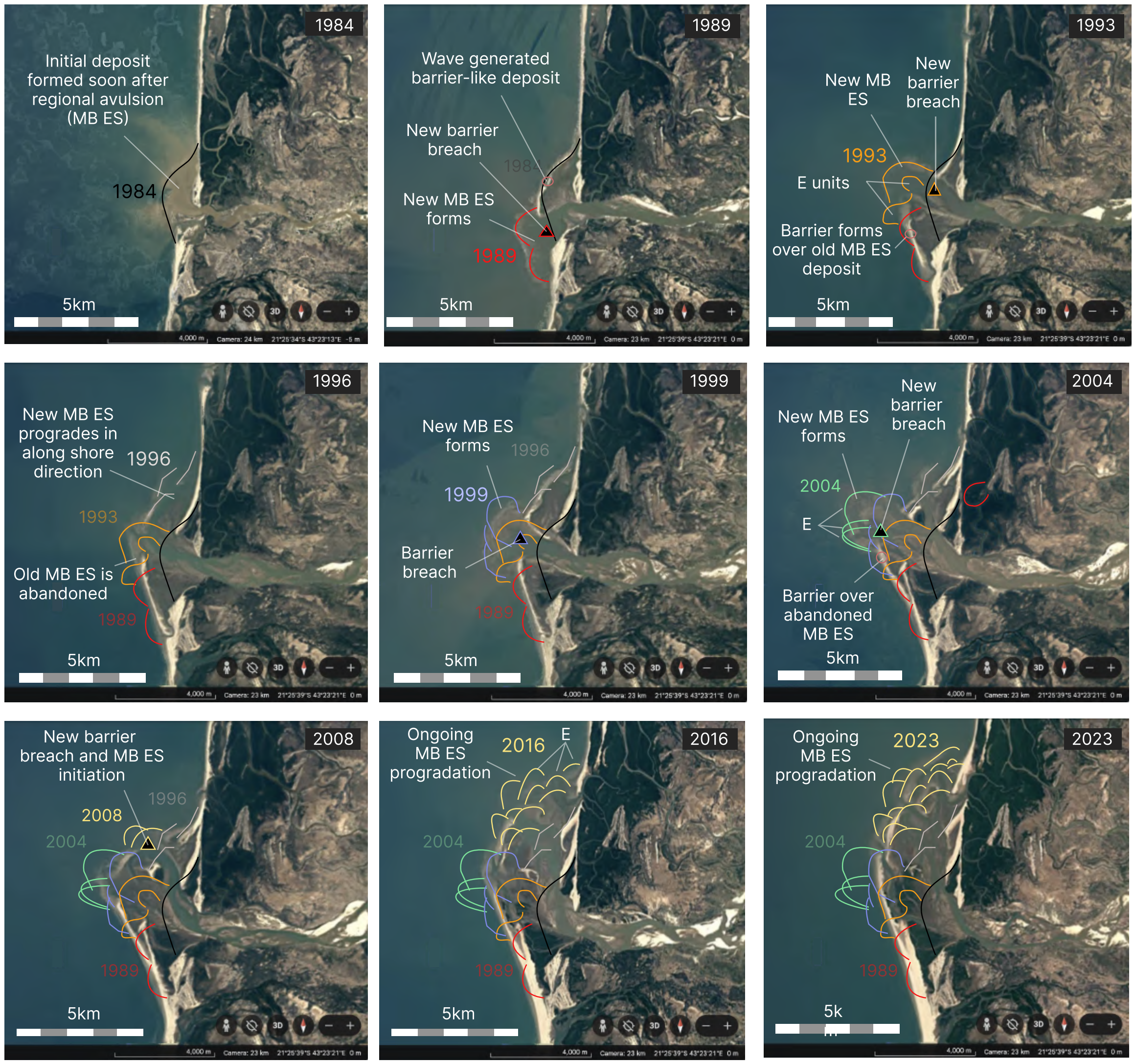

Figure 13. Progradation of the Mangoky delta in Madagascar between 1984 and 2023 following a trunk channel avulsion that shifted sedimentation to the area. The system builds through the deposition of MB ES units, which form after breaches of local wave-generated barriers on top of abandoned MB ES depocenters. At least seven MB ES units have formed in less than 40 years, resulting in 4 km of dip progradation and 10 km of strike progradation.

progradation during floods. These depocenters are partially modulated by wave action, resulting in the formation of backstepping barrier deposits.

Each depocenter remains active for several years, supplied by the same distributary channel, until a new distributary forms after a fresh barrier breach episode. An abandoned MB ES likely becomes a site of fine-grained deposition below fairweather wave base due to the presence of active river sediment point sources nearby. At least seven individual MB ES units have formed for a period of less than 40 years, each containing smaller-scale architectural complexities describable at the element (E) scale (Fig. 13). The extent of seaward topset progradation of individual MB ES clinothems ranges from hundreds of meters to over two kilometers, making these units large enough to be interpreted as parasequence-like successions by a practitioner.

DETERMINING THE HIERARCHY OF "FLOODING" INTERVALS AND THEIR ASSOCIATED SURFACES

We have described three driving mechanisms that can result in the formation of successions that can potentially be interpreted or misinterpreted as parasequences based on their shallowing upward character, presence of a capping fine-grained interval, and scale:

- Regional regressive and transgressive pulses of coastline migration related to changes in relative sea level and sedimentation.
- Fluvial point-source changes at the shoreline caused by upstream trunk distributary channel avulsions.
- Local shifts in sediment depocenter development due to levee or barrier breaches.

These mechanisms produce progradational units that can be described at the RT Sequence (i.e., RECAS-TECAS pair), ECS, and MB ES levels based on the *WAVE* Process and Architectural classification. These units are related through parent-child relationships in a hierarchical tree structure (Fig. 7). An RT Sequence contains a regional coastline progradational deposit (RECAS), which can internally contain trunk channel avulsion deposits (ECS), which, in turn, can contain levee- or barrier-breach-related MB ES (and MB ES Cluster) units.

The type of shallowing-upward succession significantly impacts predictions regarding the lateral extents, correlatability, stacking relationships, and distribution of fine-grained bounding intervals associated with these units. Therefore, special care must be taken not to directly compare units from different hierarchical levels, particularly when using them as depositional analogs.

The presence of hierarchical relationships between different types of units that may be interpreted by a worker to be parasequence like means that their bounding “flooding surfaces” can coexist within the same system and study area. Note that only the first of these mechanisms will form units that meet the definition of a true flooding surface associated with a significant increase in water depth (Van Wagoner et al., 1990). If this cannot be demonstrated, it will be better if these are treated as only potential flooding surfaces or as fine-grained intervals capping an architectural unit of an appropriate hierarchy. Figure 14 presents a strike-oriented cross section through idealized stratigraphy with flooding surfaces and fine-grained intervals formed at different hierarchical levels: RT Sequence (RECAS-TECAS pair), ECS, and MB ES.

Regressive-Transgressive Cycle (RT Sequence) Flooding Surfaces

Figure 14a shows how parasequences can be defined using maximum regressive and maximum transgressive surfaces within a regressive-transgressive cycle (i.e., an RT Sequence). The RECAS interval represents all deposits accumulated during a regional pulse of seaward coastline migration and is bounded by a maximum transgressive surface at its base and a maximum regressive surface at its top. The overlying TECAS interval includes all strata deposited during a subsequent regional landward migration of the coastline and is bounded by a maximum regressive surface at its base and a maximum transgressive surface at its top. TECAS deposits typically form laterally extensive fine-grained intervals and are often associated with the formation of transgressive ravinement surfaces. The vertical facies successions within these transgressive intervals reflect a true, regionally extensive increase in water depth, consistent with the parasequence definition by Van Wagoner et al. (1988). The TECAS interval will thus contain a true flooding surface.

ECS Fooding Surfaces

Figure 14b illustrates the formation of parasequence-like successions defined as ECS units, which are child units within a parent RECAS unit (Fig. 7). As discussed, ECS units are

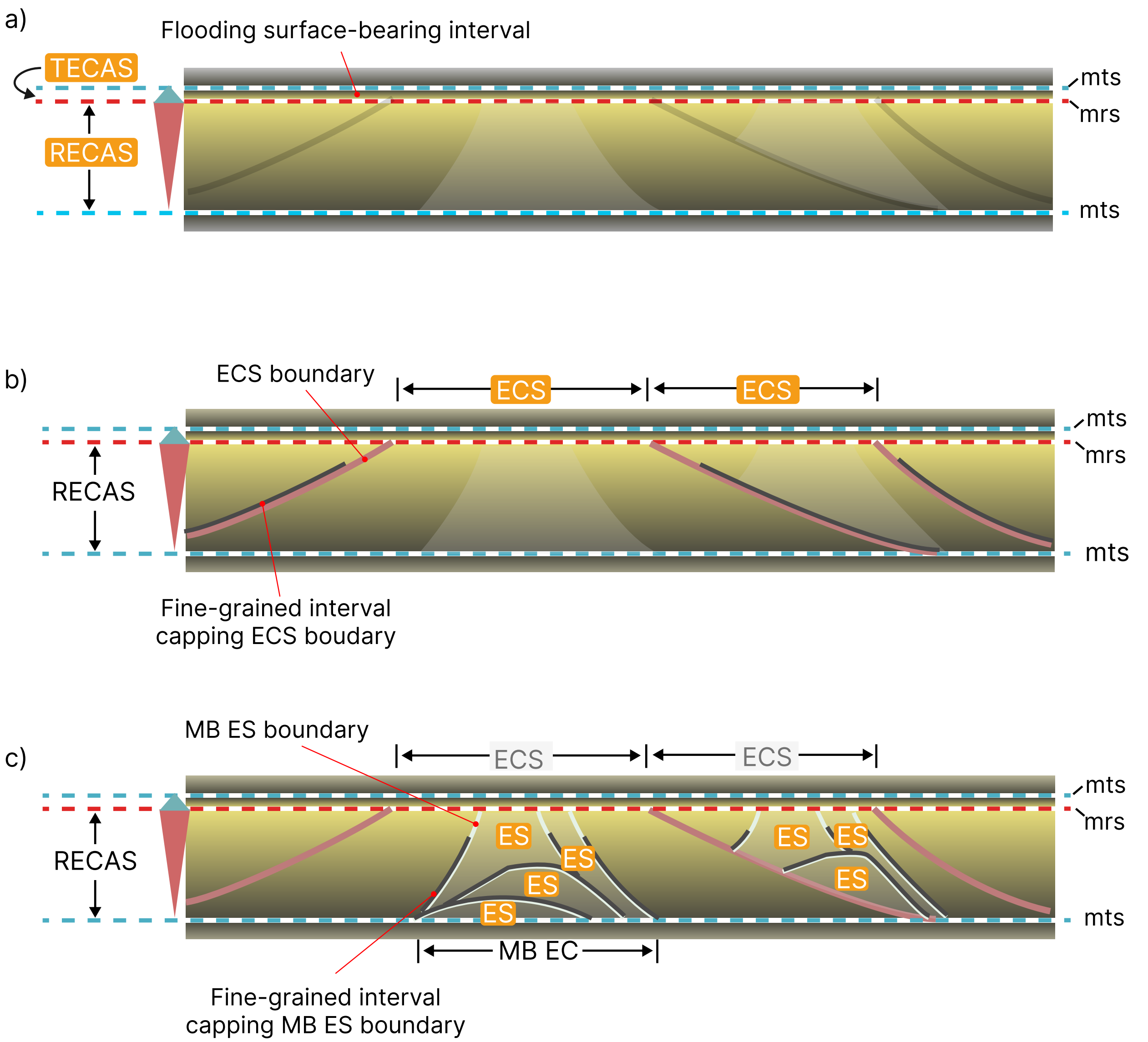

Figure 14. Idealized depositional-strike cross-section showing flooding intervals formed at three distinct depositional hierarchy levels: RT Sequence (RECAS-TECAS pair), ECS, and MB ES. a) A flooding interval associated with deposition during a regional allogenic transgression (TECAS), following deposition during a regional allogenic regression (RECAS); MRS - Maximum Regressive Surface; MTS - Maximum Transgressive Surface. b) Flooding intervals (black lines) related to autogenic delta-lobe switching (ECS) caused by trunk channel avulsion. c) Flooding intervals (white lines) associated with local MB ES deposits formed by autogenic depocenter switching in front of a river mouth. The three types of flooding intervals can theoretically coexist within the same system and can each form parasequence-like successions if occurring on a sufficient scale.

associated with distributary trunk channel avulsions on a delta plain, resulting in major sediment depocenter reorganization at the shoreline.

Each ECS unit is characterized by a shallowing-upward progradational phase that may be capped by local transgressive ravinement surfaces, associated with shoreline retreat during the abandonment phase (Fig. 5). Multiple ECS units can form within a single RECAS unit. These ECS units are often capped by fine-grained intervals, best developed on top of their outermost, distal clinoform surfaces (Fig. 5). In vertical sections, such fine-grained intervals can be potentially misinterpreted as containing parasequence flooding surfaces due to the reduction in grain size and potential changes in ichnological character (see Table 3 in Ainsworth et al, 2017). Care must be taken not to misinterpret such ECS-level flooding intervals as representing pulses of regional coastline transgression that extends beyond the bounds of the ECS unit. It is important to note that unless there is significant background subsidence in the system, these ECS-capping "flooding" intervals will not be associated with a meaningful increase in water depth. Instead, they will reflect the response of seafloor sedimentation to later switching and abandonment of depocenters.

Recognition criteria: The following characteristics can help an interpreter determine whether the fine-grained intervals capping shallowing upward successions are formed at the ECS scale. ECS capping fine-grained intervals will tend to form on a local scale and will be best developed along depositional clinoforms (Figures 5 and 14). Fine-grained intervals will often not be present in more proximal parts of the ECS (see also Howell, this volume). Autogenic ECS depocenter switching may result in predictable patterns of shallowing-upward trends between successively stacked units. Unless there has been significant subsidence between avulsions, the maximum thickness of a younger ECS unit will be limited by the space left for sediment at the time of abandonment of an older ECS units. Ichnological criteria may be used to determine whether water deepening or an abrupt shift in depocenter position has taken place. In systems where the alongshore offset between successive ECS units is significant, local ichnological stress may decrease considerably during the ECS abandonment phase, as the area becomes isolated from the river mouth's influence. Presence of ECS units can also be inferred by anomalous down-dip vertical juxtaposition of normally laterally adjacent facies associations (Element Complexes, EC) within a parent ECS (Ainsworth et al, 2017).

MB ES Fooding Surfaces

Figure 14c illustrates the presence of fine-grained capping intervals associated with local levee or barrier breach events in mouthbar-dominated areas of a delta that can potentially be misinterpreted as containing parasequence flooding surfaces. In these settings, frequent autogenic depocenter switching results in rapid progradation, followed by the abandonment of MB ES units, which are subsequently capped by fine-grained intervals (Figures 8 and 11). These MB ES units are grouped within a parent MB EC unit, which, in turn, is a child of a parent ECS unit (Fig. 7, 14).

Individual MB ES units can be interpreted as parasequence-like successions if they occur at a reasonable vertical and lateral scale and are capped by fine-grained intervals that can be potentially interpreted as parasequence flooding surfaces (Fig. 2). Care must be taken not to misinterpret such intervals as trunk-channel avulsion (ECS) or regional allogenic regressive-transgressive cycle (RT Sequence) parasequences.

Recognition criteria: The following characteristics can help in the identification of MB ES-scale successions when considering their potential parasequence interpretation. While such intervals may appear locally prominent in vertical sedimentological sections, their lateral extents will typically be limited, ranging from a few hundred meters to a few kilometers. Fine-grained intervals associated with these deposits will tend to form only along clinoform surfaces and will not tend to be associated with well-developed transgressive lag deposits. The ichnological character of MB ES units as well as their capping fine-grained intervals will tend to be stressed, because depocenter switching tends to occur over short timescales and such deposits will always be close to a river mouth. Such intervals will only show vertical, lateral and downdip stacking of units of the same type (i.e., MB ES).

MISINTERPRETATION OF PARASEQUENCE-FORMING MECHANISMS

This section discusses the practical implications of misinterpreting parasequence-forming mechanisms in a stratigraphic interval. Potential issues include the following: erroneous correlation assumptions, selecting incorrect analogues to reduce depositional uncertainty, drawing inaccurate conclusions about depositional history, and either underrepresenting or overrepresenting the time periods involved.

Flooding-surface correlation: Correlation of parasequences, particularly in the subsurface, almost always involves an element of interpretation (Fig. 2) (Colombera and Mountney, 2020). Such decisions are informed by the mental depositional models held by the interpreter. Misinterpretations of the parasequence-forming mechanism will therefore directly impact choices made during flooding-surface correlation. Note that if the formative mechanism cannot be objectively determined based on available data, the interpreter should consider alternative scenarios that capture the full range of possibilities until more information becomes available.

Analog selection: Parasequences are often crucial for understanding fluid flow in the subsurface, which requires reasonable assumptions to be made about the thickness and lateral extent of flooding intervals. When data are limited, depositional analogs are frequently used to guide such decisions (Colombera and Mountney, 2020, Ainsworth et al, 2020). It is essential to choose parasequence analogs formed at the same hierarchical level and by the same formative mechanism. For example, using analogues formed by regional pulses of regression and transgression (RT Sequence) for intervals created by channel levee breaches in a fluvial-dominated delta (MB ES) could result in greatly exaggerated predictions of flooding interval extents. This could lead to unreasonable correlation decisions, such as forcing layer-cake correlations in situations where flooding surfaces have clinoform shapes and are mappable only over short distances. See Ainsworth et al. (1999; 2010) and Gani and Bhattacharya (2005).

Depositional history: Incorrect assumptions about parasequence-forming mechanisms can lead to significant misinterpretations of an interval's depositional history. For example, interpreting an ECS interval as a RECAS deposit would result in the erroneous identification of additional regional regressive-transgressive cycles that never occurred. Conversely, mistaking a RECAS deposit for an ECS interval would lead to the reverse misinterpretation. The most problematic scenario arises when MB ES parasequence-like successions are misinterpreted as ECS- or RECAS-level deposits. Relating cycles identified from such local-scale deposits to more regional processes can introduce substantial errors in interpretation. This can distort the understanding of the temporal and spatial dynamics of the depositional system.

Parasequence timing: An obvious interpretation error that can result from misinterpreting the parasequence-forming mechanism involves the timing of unit formation. Potential errors in time estimation can be significant and off by several orders of magnitude. In the most extreme scenario, MB ES units formed over the course of months to several years in a rapidly prograding delta might be mistakenly interpreted as RECAS intervals, which may be deposited over timescales of tens of thousands of years.

LESSONS FOR PARASEQUENCE INTERPRETATION BASED ON MODERN AND ANCIENT SYSTEMS

The notion of parasequences originated from ancient outcrop and subsurface studies aimed at improving reservoir interval characterization (Wan Wagoner et al, 1988, 1990). As a result, parasequence concepts have been shaped by the perspectives of the outcrop and subsurface geologist.

Parasequences are typically mapped using vertical outcrop, core, or wireline log data, which are then correlated across vertical cross-sections, often in dip-oriented views (e.g., Van Wagoner et al., 1990, Garrison and van den Bergh, 2004, Zhu et al., 2012, Lin et al., 2019; Pattison, 2019). Determining depositional hierarchies based solely on cross-sectional data can be challenging, leading to parasequences being defined at the hierarchical level that appears most apparent at a given location. In some areas, this may correspond to the regressive-transgressive cycle scale, while in others, it may be the much smaller MB ES scale.

To fully understand the link between 3D stratigraphic architecture and parasequence development, it is essential to integrate insights from both modern and ancient systems. Comparing the advantages and disadvantages of these types of datasets can help improve our understanding of parasequences (Fig. 15).

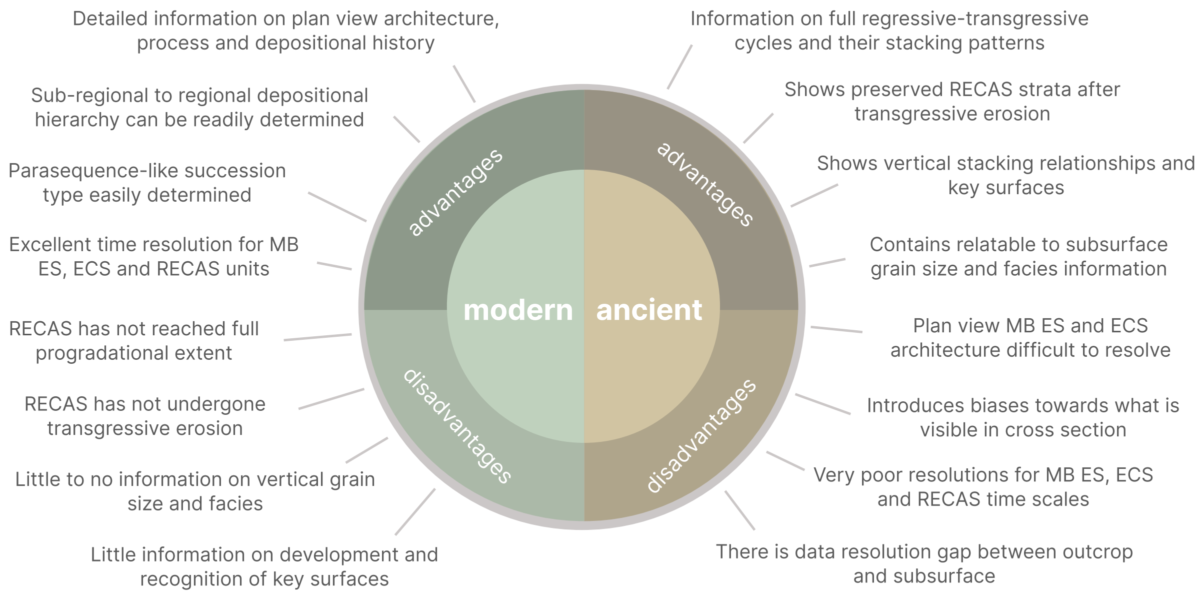

Figure 15. Summary of main advantages and disadvantages of modern and ancient systems for studying the depositional hierarchy of parasequence-like successions.

Advantages of ancient outcrop and subsurface data over use of Holocene datasets

Ancient data has the following advantages over Holocene data:

Vertical stacking can be readily determined: Ancient case studies are the best source of information on the vertical stacking of stratigraphic units, the key surfaces that bound them, and the facies that characterize them. They provide insights into how vertical facies successions form and relate to parent stratigraphic units, teaching us how key surfaces develop and how they can be recognized. In contrast, modern studies often offer less information on facies variability and recognition criteria that can be directly applied to subsurface datasets.

Shows complete regressive-transgressive cycles: Ancient case studies show sediment accumulation of complete regressive-transgressive cycles (RT Sequences), allowing us to observe preserved units and map the full extent of their maximum regressive and transgressive surfaces. They provide insights into how these cycles build over time, how trends develop within successive cycles, and how larger-scale units such as systems tracts and stratigraphic sequences are constructed. Parasequence lessons from Holocene systems, on the other hand, are limited to observations made within a narrow geological timeframe. Most Holocene RECAS intervals, in contrast, have prograded only since the stabilization of sea level in the mid-Holocene and have not completed their current regressive cycles. Moreover, all such units are deposited during an interglacial period associated with high frequency and amplitude eustatic changes of sea level.

Shows preserved stratigraphy: Ancient case studies show the preserved stratigraphy of intervals. For example, strata observed in outcrop or subsurface cross-sections show the preserved thickness of RECAS units if they have been eroded by transgressive ravinement (see Posamentier and Allen, 1999). Observations of RECAS units in the modern, on the other hand, show the original stratigraphy which can be potentially partially or fully eroded during a future transgression (Ainsworth et al., 2017). It must be noted that modern RECAS intervals do preserve local transgressive intervals formed at the scale of ECS formation (Fig. 6). Depending on depth of ravinement and rate of subsidence, modern RECAS deposits can also be fully preserved.

Is easily relatable to subsurface data: Observations from ancient outcrop and subsurface case studies are directly relatable to vertical data typically collected from subsurface intervals. While vertical facies information is sometimes available from Holocene case studies, it tends to be rarer, making direct comparisons between subsurface observations and modern mapping more challenging.

Advantages of Holocene Architectural Data over Ancient Outcrop and Subsurface Data

Holocene data has the following advantages over ancient outcrop and subsurface data:
Plan view architecture is readily determined: Modern case studies provide valuable insights into the evolution of systems in terms of plan-view architecture (e.g., Giosan et al, 2005; Stefani and Vincenzi; 2005; Vella et al, 2005; Somoza and Rodriguez-Santella, 2014; Rossetti et al., 2015; Panin et al, 2016; Nanson et al, 2013; Lane et al., 2017; Ainsworth et al, 2019) . Mapping depositional features such as beach ridges and active and abandoned channels often allows for the detailed reconstruction of a system's depositional history, where lateral shifts of depocenters (ECS) and avulsions can be easily identified (Fig. 6). Historical aerial imagery reveals how distributary channels and shallow portions of mouth bars evolve over years to decades, enabling the mapping of MB ES deposits (Figures 10, 13). In contrast, resolving plan-view architectural changes in ancient cross-sections is often more challenging (Ainsworth et al, 2017), where the hierarchical level of a flooding interval and important surfaces with a local cryptic expression may be misidentified.

Has better chronostratigraphic resolution: Modern case studies offer better chronostratigraphic resolution, allowing us to determine whether ECS and MB ES deposition occur on timescales of tens, hundreds, or thousands of years (e.g., Correggiari et al., 2005; Giosan et al, 2005; Nanson et al, 2013; Lane et al., 2017, Ainsworth et al., 2019). Achieving this level of resolution in ancient deposits is not possible, making it challenging to use dating methods as a tool to distinguish between parasequence forming mechanisms.

Has better data continuity at different scales: Modern case studies provide better continuity of data across different scales of observation, enabling the viewing of MB ES deposits within larger-scale ECS deposits within regional RECAS deposits (Nanson et al, 2013, Lane et al., 2017; Ainsworth et al., 2019). In contrast, outcrop and subsurface data often suffer from data availability issues at certain scales. Many continuous outcrop architectural studies are of limited lateral extent which allows studying local but not regional architecture.

Allows determining relationships between process and architecture: An additional benefit of using Holocene systems to understand stratigraphic architecture is the abundance of data from a wide range of depositional environments (e.g., Nyberg and Howell, 2016). This wealth of information makes it much easier to study the link between process, architecture and other depositional variables. Such relationships are always inferred in ancient case studies, which can lead to problems of circular reasoning, as well as selection bias based on outcrop availability. One can argue that the development of parasequence concepts may have been different had the Cretaceous strata of the Western Interior in the Book Cliffs area been more tide dominated or was deposited under lower accommodation conditions.

The Benefits of Using a Combined Modern-Ancient Analogue Approach

Using key lessons from both modern and ancient analogues provides the best opportunity for understanding hierarchies of successions that can form shallowing upward intervals that can resemble parasequences. Modern analogues offer excellent information of plan view evolution of MB ES units, ECS units and their relationships to parent RECAS deposits. These analogues are particularly useful for understanding the links between depositional processes and resultant architecture. Ancient systems, on the other hand, provide critical insights into vertical grain size and facies trends, the recognition of key surfaces, and unit preservation (see Ainsworth and Vakarelov, this volume).

By integrating insights from both modern and ancient case studies, we can improve assumptions made about the size, depositional character and timing of parasequence formation. Geologists, trained to think in terms of geological time, often underestimate the rapid progradation potential of shallow marine systems. Many Holocene RECAS deposits were formed through regional coastline progradation of many tens of kilometers over the last 6,000 years (e.g., Ta et al., 2002; Allison et al, 2003; Tanabe et al, 2006; Giosan et al., 2018). Delta lobes (ECS) have locally advanced their shorelines by many kilometers over hundreds of years (e.g., Correggiari et al., 2005, Ainsworth et al., 2019). Moreover, local progradation of several kilometers can occur within a mouth bar-delta front interval in just years to a few decades—a scale that can correspond to a parasequence-like succession visible across an entire outcrop.

Modern Mitchell River Delta - Campanian Bearpaw–Horseshoe Canyon Formation transition comparison.-

Detailed outcrop-based architectural studies often align well with observations from modern systems when viewed at the same scale. A comparison of the plan-view architecture of mouth bar deposits at the mouth of the Mitchell River delta, Gulf of Carpentaria, Queensland, Australia (Nanson et al, 2013, Lane et al, 2017, 2023), with that of a regressive-transgressive cycle (RT Sequence) from the Campanian, Bearpaw–Horseshoe Canyon Formation transition, exposed near Drumheller, Alberta, Canada, reveals that both intervals were deposited under similar mixed-influence process conditions and progradational water depth (Ainsworth et al, 2016, 2017).

The mouth bar area in front of the Mitchell River mouth reveals small progradational units (Mouthbar Elements, MB E), which group into distinct MB ES units (Fig. 16 top). MB E units within a parent MB ES are formed by the same local terminal distributary channel, which remains active for a period in the same part of the mouth bar area. A new MB ES depocenter forms when a terminal distributary is established at a new location within the parent MB EC. The parent MB EC represents the sedimentary band composed of all prograding mouth bar and delta front deposits formed by sediment supplied by the main distributary over time (Fig. 16) (see also Figure 20 in Ainsworth et al, 2016). In avulsive systems, MB EC deposition will initiate after a trunk channel avulsion forms a new sediment depocenter at a shoreline. It is important to note that the aerial imagery only shows the shallowest portions of all discussed architectural units and that in reality they extend further subaqueously in both dip and strike directions.

Similar architecture can be observed in the Drumheller ancient cross section, where both MB ES and MB E units are identifiable within a parent MB EC deposit (Fig. 16 – cross-section view) (based on Ainsworth et al, 2016). Compensationally stacked, lens-shaped MB E units are found internal to larger, lens-shaped MB ES deposits. Both the MB E and MB ES lens-shaped deposits likely form lobate shapes in three dimensions. MB ES deposits, which internally coarsen upward, are locally capped by mappable fine-grained and heterolithic intervals that preferentially form along their distal (deeper) portions (Fig. 16). In more proximal (shallower) areas, such fine-grained intervals do not develop and MB ES boundaries become characterized by sand-on-sand

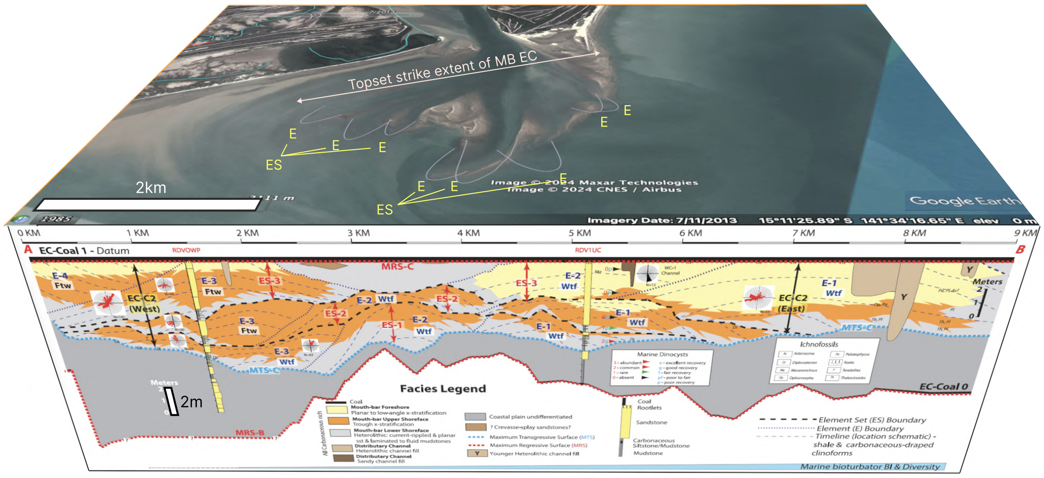

Figure 16. A planview-cross-section comparison diagram showing a modern deposit alongside an ancient cross-section, both at the same horizontal scale. (Top) The present-day mouth bar area in front of the Mitchell River mouth, Gulf of Carpentaria, Australia, illustrating the topset strike extent of the Mitchell delta Mouthbar Element Complex (MB EC) and several examples of mouth bar elements (E) forming within active mouthbar element sets (ES). (Front) An outcrop-based cross-section through a regressive-transgressive cycle from the Campanian Bearpaw–Horseshoe Canyon Formation transition, exposed near Drumheller, Alberta, Canada (details in Ainsworth et al., 2016). This interval, deposited in comparable settings and under similar process regimes, exhibits similar internal element (E) and element set (ES) architectures, occurring on comparable horizontal scales. Note that ES units can be capped by fine-grained intervals and potentially interpreted as parasequence-like successions.

contacts. It is important to note that while vertical sections may show coarsening-upward intervals capped by finer-grained layers, these changes do not reflect shifts in relative sea level but rather local autogenic shifts in sediment depocenters.

We can examine the cross section in terms of identifiable parasequence-like successions. The entire regressive, mouth-bar-dominated interval visible in the cross section is bounded by a maximum transgressive surface below and a maximum regressive surface above, forming a RECAS unit. This RECAS unit, which is regionally mappable, is overlain by a coal-bearing, regionally mappable transgressive TECAS interval, making it a strong candidate for interpretation as a regional (likely allogenic in origin) parasequence (RT Sequence).

The coarsening-upward MB ES units can also potentially be interpreted as being parasequence-like, especially in areas where they are bounded by well-developed fine-grained intervals. Although the vertical scale of these deposits is relatively small, this is a result of the shallow progradational depth of the system (<10m) related to the low shelf-gradient: it can be safely assumed that such deposits would have likely been thicker had the progradational depth been greater (higher shelf gradient; See Ainsworth et al., 2017, 2020). Regional studies have also indicated that the entire MB EC interval was likely part of an ECS unit, which includes additional lobe element complex (LO EC) deposits (Ainsworth et al, 2015, 2016, 2017). As previously discussed, ECS units can also form successions that have the character of parasequences. The studied interval therefore shows at least two, and potentially three, architectural levels that can be interpreted as forming potential parasequence-like successions at the same location: RT Sequence (RECAS-TECAS pair), MB ES and ECS. Each depositional unit type will have different expected dimensions and correlation trends.

Subsurface scenarios based on the same architecture: Let us examine how similar architecture can be interpreted based on two limited subsurface data scenarios where depositional hierarchies are not considered. If an interpretation is made based on a single data point located at Kilometer 1 in Fig. 16, three separate parasequences can be defined. This can result in a depositional conceptual model containing three separate reservoir units vertically separated by shale intervals across a field. If, on the other hand, the single data point was located at Kilometer 7 in Fig. 16, only a single parasequence may be interpreted and a tank-like reservoir depositional model may be considered. Ideally, under both scenarios, if facies information suggested presence of mouth bar deposits (MB EC), this should have resulted in the generation of more realistic depositional scenarios. These should have included the presence child MB ES units governing local heterogeneity distribution, and a parent RECAS-TECAS pair interval describing the regional distribution of the deposit.

INTERPRETATION OF SMALL-SCALE, PARASEQUENCE-LIKE SUCCESSIONS IN THE STRATIGRAPHIC RECORD

Detailed architectural work in many outcrop-based case studies, characterized by mouth bar and delta front-bearing vertical successions, often reveals the presence of small-scale depositional units that are frequently treated as parasequences (e.g., Zhu et al, 2012, Fielding, 2015, Korus and Fielding, 2017). In vertical successions, these intervals typically occur on scales of meters, coarsen upward, and are capped by finer, more distal strata, which often forms along clinoform surfaces. We argue that it is plausible that some of these successions may represent MB ES or ECS units rather than allogenic regressive-transgressive cycles (RT Sequences) and may thus form at much higher temporal frequencies and progradational rates than tends to be assumed.

We compare two cross section examples of mouthbar and delta front-bearing strata from the Turonian Ferron Sandstone to modern case studies that develop similar scales of architecture over time periods of hundreds of years or less.

Cretaceous Ferron - Po delta comparison

A detailed study of the Turonian Ferron Notom Delta Complex has identified forty-three parasequences, grouped into eighteen parasequence sets and five high-frequency sequences (Zhu et al., 2012) (Fig. 17a). Chronometric analysis of age-dated bentonites suggests that the entire interval was deposited over a period of 600,000 years. Depositional sequences 6 to 3 in the Ferron cross section contain numerous prodelta-facies dominated parasequences, which occur on vertical scales of meters and lateral scales of several kilometers. Many of these parasequences exhibit downlap and onlap relationships relative to underlying strata, forming lensoid shapes in cross section. Additionally, successive parasequences often display overlapping, laterally compensational depositional patterns.

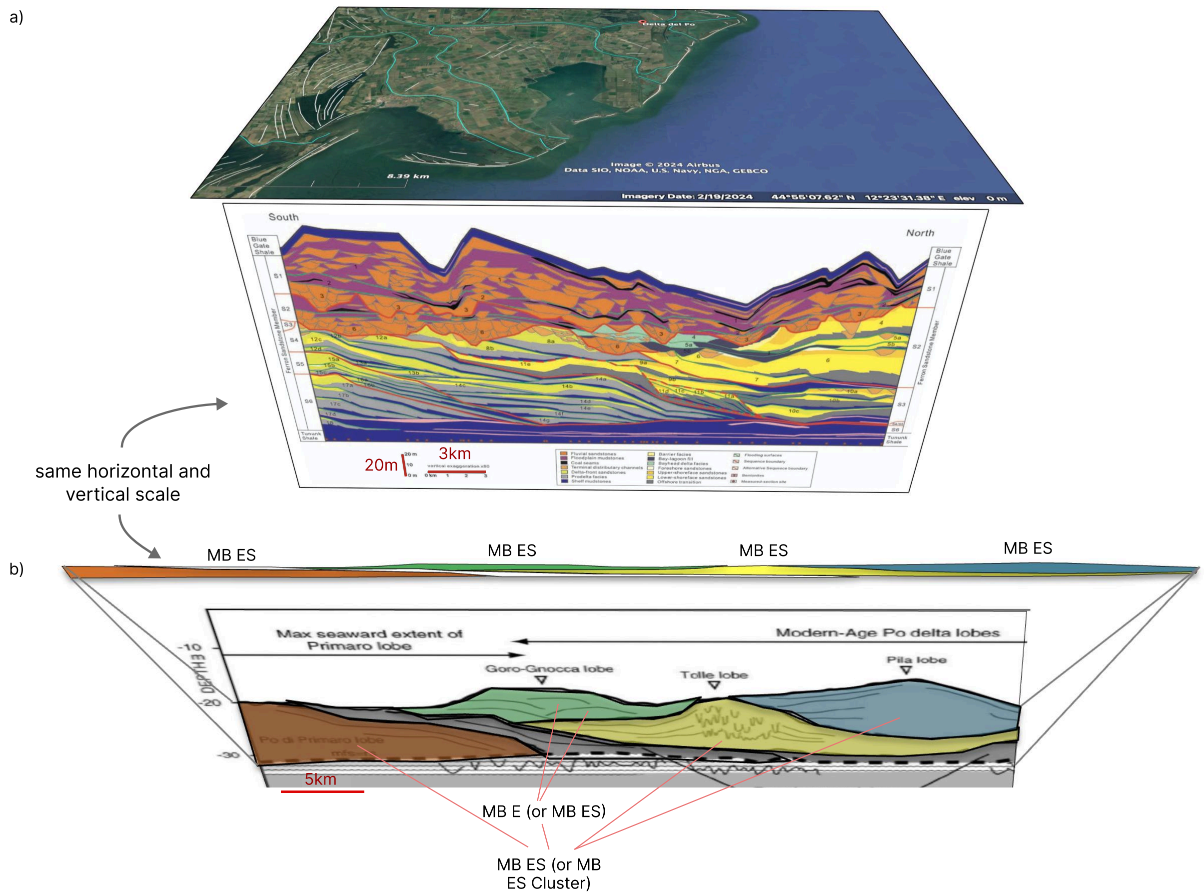

Figure 17. Comparison between the architecture of the present-day Po delta and parasequences mapped in an outcrop-based cross-section from the Cretaceous Ferron Sandstone, Utah. a) A planview-cross-section comparison diagram showing the Po delta (top) and an interpreted cross-section from the Ferron Notom Delta Complex at the same horizontal scale (see Zhu et al., 2012 for cross-section details). b) Interpreted units based on a Chirp-sonar profile taken seaward and sub-parallel to the present-day Po coastline (see Correggiari et al., 2005 for more details). The top section is shown at the same horizontal and vertical scales as the Ferron example. The deposition of these units is directly linked to the positions of river outlets in the Po delta and is autogenic in origin. All units were deposited in less than 500 years based on the interpreted Po delta depositional history.

The small-scale parasequences in sequences 6 to 3 are interpreted by Zhu et al. (2012) as representing distinct regressive-transgressive cycles (parasequences). Flooding surfaces are identified by "mud-on-sand" contacts, indicating a sudden increase in water depth, and parasequences are used to infer shoreline trajectories within parent sequences.

The architecture of the Ferron can be contrasted with present-day plan view and subsurface data from the Po delta (Fig. 17b top). In plan view, the Po delta is characterized by multiple distributaries delivering sediment to various locations along the shoreline, forming separate sediment depocenters. Internally, the Po delta is built by “clinothems” with a vertical scale of under 30 meters, reflecting the progradational depth of the system (Correggiari et al., 2005). This architecture is part of the present-day Po delta, which has prograded approximately 30 kilometers over the last 500 years (circa 60 meters per year), with its evolution traceable through historical maps (Correggiari et al., 2005).

An interpreted Chirp-sonar profile seaward and sub-parallel to the present-day coastline of the Po delta (Correggiari et al., 2005) is also included in Figure 17b. The profile reveals the internal architecture of the prodelta portion of the Po delta. This profile is also shown at the same vertical and horizontal scales as the Ferron cross section. Identifiable seismic stratigraphic units exhibit lensoid shapes, onlap and downlap relationships relative to underlying units, and laterally overlapping vertical stacking patterns (Correggiari et al., 2005). The deposition of these units is directly linked to the positions of river outlets of the Po delta, with periods of relative growth corresponding to the varying activity of these outlets over time (Correggiari et al., 2005). These units can therefore be interpreted as autogenic in origin MB ES (or MB ES Cluster) deposits.

Alternative interpretation of ancient interval: There is a significant resemblance in the scale and character of many Ferron parasequences to the units mapped in the modern Po system. It is worth considering whether some of the Ferron parasequences could alternatively be explained by similar autogenic processes, suggesting much more rapid rates of sedimentation, as suggested by the following: (1) The units occur on a similar vertical and horizontal scale and show similar downlap, onlap, and vertical stacking relationships. (2) The formation of mud-on-sand contacts can also be explained by lateral shifts in depocenter deposition (MB ES or MB ES Cluster), particularly in distal delta front and prodelta areas. Flooding surfaces capping older Ferron parasequences do not appear to be associated with significant changes in depositional character (e.g., an abrupt increase in bioturbation), potentially suggesting ongoing deposition. (3) It may be difficult to reconcile why fluvial-dominated parasequences prograde on scales of hundreds of meters to a few kilometers over an entire regressive-transgressive cycle, when such deposits are routinely shown to locally prograde over similar distances at much faster rates in Holocene systems.

Cretaceous Ferron - modern Mangoky delta comparison

An interesting comparison between an ancient and modern interval can be made using another well-studied Ferron Sandstone outcrop section and a rapidly prograding portion of the Mangoky delta in Madagascar (Fig. 18). A portion of a cross section from Fielding (2015) and Korus and Fielding (2017) reveals the detailed high-resolution sequence stratigraphic architecture of an 8 km dip-oriented, 50 m thick interval, featuring numerous sandstone intervals capped by fine-grained strata (Fig. 18 front). These intervals are informally described as sandstone bodies, which are numbered and locally correlated. Sandstone bodies 1 to 15 belong to a single clinoform set, exhibiting clear clinoform geometries with identifiable topsets, foresets, and bottomsets (Korus and Fielding, 2017). Each sandstone body is shown to be capped by a "flooding surface" (see Fig.13, Korus and Fielding, 2017).

Korus and Fielding (2017) interpret individual sandstone bodies as "fundamental (high-frequency) sequences," and the entire clinoform set as a sequence set. This interpretation is based on: the identification of bounding surfaces resembling sequence boundaries, marked by scour surfaces at the bases of cross-bedded sandstone bodies in some units; subaerial exposure on top of medial delta-front facies in sandstone body 13; downdip association with the bases of large gully fills interpreted as related to the falling stage of lowstand cycles.

Figure 18 top shows the timeline evolution of a rapidly prograding portion of the Mangoky delta in Madagascar since 1984, displayed on the same horizontal scale as the Ferron example. The interval demonstrates that in only 38 years, the shoreline prograded over 4 kilometers in the dip direction (circa 105 meters per year) and 10 kilometers in the strike direction (circa 260 meters per year) (Fig. 13). Mapping the system’s detailed evolution reveals that it builds through initiation of new lobate mouthbar depocenters after barrier breaches by distributary channels near the main river mouth. These depocenters prograde rapidly and then get abandoned, which is

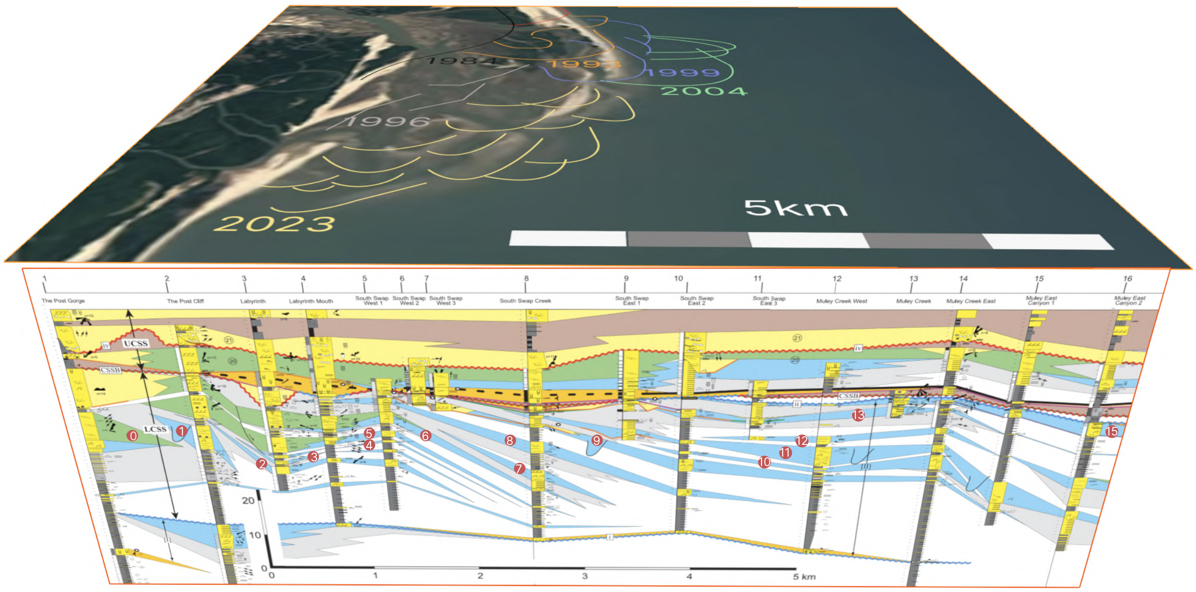

Figure 18. A planview-cross-section comparison diagram between the architecture of the present-day Mangoky delta, Madagascar, and an outcrop-based cross-section from the Cretaceous Ferron Sandstone, Utah, USA (see Korus and Fielding (2017) for cross-section details). The Ferron interval (front) is interpreted to contain numerous high-frequency sequences (indicated by red circles). The interpreted Mangoky interval (see Figure 13 for details) shows the planview positions of seven MB ES units, differentiated by color. While not suggesting a direct depositional analogue, this comparison highlights the contrast between small-scale parasequence-like successions identified in detailed outcrop studies and the rapid progradation observed in many modern systems. The Mangoky delta has prograded four kilometers in the dip direction in less than 40 years and contains MB ES units that may resemble parasequences in cross-section.

accompanied by formation of a local barrier over the former deposit. Depocenter abandonment is associated with the compensational growth of a new depocenter at a different location within the same parent MB EC. The studied interval contains at least seven distinct depocenters (MB ES or MB ES Clusters). The interpreted MB ES deposits visible on the aerial map represent only the shallowest, most landward portions of these three-dimensional sediment bodies. These units extend subaqueously in both the dip and strike directions and likely form well defined clinoforms.

Alternative interpretation of ancient interval: It is interesting to contrast the current interpretation of the discussed Ferron interval, which suggests presence of numerous high-frequency sequences (regressive-transgressive cycles) formed over geological time, with the architecture of the Mangoky delta, which was formed by deposition of MB ES scale units over several decades. The Mangoky interval should only be considered as a partial analogue that illustrates how parasequence-like successions can form over decades. While Korus and Fielding (2017) do provide evidence for their interpretation, it appears somewhat tentative. Other lines of evidence may point to presence of much more rapid rates of progradation: (1) The MB ES units mapped in the Mangoky delta occur on scales quite similar to the sandstone bodies observed in the Ferron interval, suggesting that such rates of progradation should be considered as possible in an ancient system; (2) Sedimentary sections do not show evidence of an abrupt increase in bioturbation associated with flooding surfaces, which might be expected if the coastline had backstepped; (3) The abundance of soft sediment deformation and growth faulting suggests rapid rates of progradation, which raises the question of why the shoreline prograded so little during each regressive-transgressive cycle. (4) Units appear to be of the same type across many cycles.

RECOMMENDATIONS AND CONCLUSIONS

Despite criticisms, the term "parasequence" has proven convenient and will likely remain in use by the community. The issue of parasequences potentially forming at different depositional hierarchy levels is nonetheless significant, as insights from one level may not directly apply to another. Misinterpreting a parasequence forming mechanism can lead to errors in correlation, depositional history interpretation and modeling.

In this context, we recommend that the term "parasequence" be constrained to two types of usage:

Interpretive: When "parasequence" is used to denote a sedimentary package formed by one of the specific driving mechanisms discussed in this paper, it should exclusively refer to regionally significant regressive-transgressive deposits of likely allogenic origin (i.e., RT Sequences based on the *WAVE* Process and Architectural Classification). This interpretation aligns closely with the original definition of the term and is most widely accepted by practitioners. In this context, a parasequence represents deposits formed during pulses of regional seaward and landward coastline migration, with flooding surfaces formed during periods of regional water deepening associated with transgression. See also discussion in Howell (this volume).

Purely descriptive: The only other acceptable use of "parasequence" should be in a purely descriptive sense that is divorced from any implication of formative mechanisms. This informal usage should be limited to local scales and should refer to sediment packages with specific grain size trends, facies or log motif characteristics, such as a coarsening-upward intervals being capped by a fine-grained layer formed at sufficient scale. The descriptive sense of the term must be clearly communicated: to avoid confusion this paper referred to such intervals as *parasequence-like successions* or '*successions that resemble parasequences'*. Such intervals can also be referred as '*candidate parasequences'* if it is made clear that the parasequence in this case does not refer to a particular mechanism.

We recommend that sedimentary packages that can potentially be interpreted to have been most-likely formed by autogenic, intra-depositional system mechanisms (e.g., trunk distributary channel avulsion, local levee or barrier breach), even if they exhibit parasequence-like characteristics, should be named using alternative terminology. This sentiment was echoed by Miall (2010) who pointed out that referring to autogenic deposits with a term that includes the word "sequence" as a part of it should be considered misleading. In other words, if units can be clearly interpreted as RECAS-TECAS pairs forming RT Sequences (regional deposits), they can be called a parasequences. If, on the other hand, units can potentially be interpreted as either RT Sequences or ECS deposits, both interpretations should be considered as plausible and the parasequence term should be avoided.

Using parasequences to refer to units interpreted to have formed by autogenic mechanisms such as the ones discussed in this paper is not recommended. As discussed, such units will be influenced by local depositional complexities and interpretation uncertainties. The number of parasequence-like successions will, for example, be strongly affected by the relative importance of fluvial versus wave and tidal processes. Additionally, different numbers of such parasequence-like successions may end up being defined in mouth bar areas (MB EC) compared to adjacent lobe areas (LO EC) even when these are influenced by similar coastal processes. Definition of units in such intervals will therefore greatly benefit from using nomenclature that considers depositional environments, their architecture, and any depositional hierarchical relationships that may be present.

These issues are reflected by the reluctance of many researchers to refer to units as parasequences, even when they have characteristics of parasequences. For example, as discussed, Korus and Fielding (2017) referred to parasequence-like successions in the Ferron as "sandstone bodies," despite these being capped by “flooding surfaces”. Plink-Björklund (2008) described intervals resembling parasequences in the Upper Cretaceous Campanian Chimney Rock Tongue as "clinoform sets." There is a long history of parasequences-like successions being described as allomembers (e.g., Bhattacharya and Walker, 1991, Ainsworth, 1991, 1994, Plint, 2000, Bhattacharya and Willis, 2001). The fluvial-dominated Panther Tongue delta, a well-studied interval that coarsens upward and is capped by a regionally correlatable ravinement surface, has been interpreted as a “forced regressive deposit” (Posamentier and Morris, 2000). Even though individual coarsening-upward packages occurring internal to the interval were referred to as "bedsets" by Enge et al. (2010), Atlas et al. (2023) named the same units from the same outcrops "depositional cycles" and clearly noted that these were capped by flooding surfaces and that they meet the definition of parasequences. While avoiding parasequence terminology sidesteps the challenges associated with its definition and use, the proliferation of different descriptive terms does not resolve the issues related to architectural hierarchies.

The best approach for addressing parasequence-like successions formed by mechanisms operating at different depositional hierarchical levels is to adopt a hierarchical depositional scheme. While the original definition of a parasequence includes child categories like bedsets and beds (Van Wagoner et al., 1990), there are three issues with relying solely on these terms: (1) Somewhat surprisingly Van Wagoner et al. (1990) referred to the Campbell (1967) definition of a bedset, which is "two or more superposed beds characterized by the same composition, texture, and sedimentary structure”, with this definition closely resembling the McKee and Weir

(1953) definition of a coset. This definition of bedset should therefore not permit usage of the term to describe a coarsening-upward interval containing different bed types. (2) The three-level hierarchy of parasequence, bedset and bed is insufficient to describe the full range of observable parent-child relationships in shallow marine systems. As discussed in this paper, an allogenic parasequence (RECAS) may contain river-avulsion-related units (ECS), which can internally contain mouth bar-dominated intervals (MB EC) formed by individual mouth bar depocenters (MB ES), each built by distinct growth sedimentation pulses (E). One can argue that it should be the individual elements (E) which should contain the beds and bedsets of Campbell (1967). (3) Different numbers of bedsets can form in different portions of a depositional system along the same stretch of coastline, with more bedsets present in mouth bar areas (MB EC) and fewer in adjacent lobe areas (LO EC).

In this paper, we have used the *WAVE* Process and Architectural Classification of Vakarelov and Ainsworth (2013) to describe the different levels of architecture that can form successions that can resemble parasequences. This classification effectively captures both the hierarchical level and the architectural type of the deposit, resulting in terminology that minimizes confusion. For instance, referring to an interval as a RECAS deposit clearly denotes a regionally deposited allogenic unit, while an ECS deposit necessarily indicates the presence of an avulsion-related formative mechanism. Such an ECS unit is clearly distinct from an MB ES-scale deposit, which is formed by an autogenic process at the distributary channel-mouth scale. The process-based aspect of the classification (Ainsworth et al., 2011) also allows effective communication of the depositional process regime during formation. For example, the coarsening-upward Panther Tongue bedset (depositional cycle) intervals discussed earlier can be described as built by F-MB ES deposits, likely forming parts of larger-scale MB ES Clusters (see discussion in Ainsworth and Vakarelov, this volume). This will clearly communicate both the depositional process (F) and the architectural units being described (MB ES or MB ES Cluster). Such units cannot be formed by regional trunk channel avulsion or an allogenic change in relative sea level and rates of sediment supply. The entire Panther Tongue progradational interval capped by a transgressive ravinement surface will form a RECAS interval capped by a TECAS interval, forming a Parasequence or an RT Sequence. See Ainsworth et al. (2015, 2016, 2017, 2020) for ancient case studies that effectively use this terminology to describe different architectural hierarchies.

This study illustrated how different formative mechanisms can potentially result in the generation of parasequence-like successions at depositional hierarchy levels: RT Sequence (RECAS-TECAS pair), ECS, MB ES. We further demonstrated that parasequence-like successions in mouthbar-delta front dominated intervals can be formed over very short time periods of years to hundreds of years. Misinterpretation of such mechanisms, especially in a subsurface setting with limited data, will have important implications for decisions involving correlation of flooding surfaces, predictions of lateral extents of sandstone units and flooding intervals, depositional history, temporal frequency, as well as static and dynamic modeling for parasequence-bearing intervals. We have argued that the term “parasequence” should only be reserved for regionally significant regressive-transgressive units (RT Sequences) of likely allogenic origin, which tend to occur over geological time, and that alternative terminology should be used for units potentially interpreted to have been formed by autogenic mechanisms (ECS, MB ES), which occur over historical time.

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